Snohomish County
Planning & Development Services

Revised Draft Summary of Best Available Science for Critical Areas

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Snohomish County

Planning & Development Services

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Executive Summary

Snohomish County's historical initiative and abiding concern for environmental quality has led to responsible and aggressive protection of environmentally sensitive areas. These front-line actions have been central in sustaining the natural beauty and quality of life in this region. Working in partnership with the tribes, community groups, and state and federal agencies, the County has preserved and restored salmon habitat to ensure the perseverance of this vital cultural, economic, and ecological natural resource. The County's implementation of buffers on aquatic areas has protected essential fish and wildlife habitat and natural functions. The County has made significant progress in protecting the natural environment, but as demands on these resources grow we need to take additional actions.

The primary challenge facing environmental protection in Snohomish County is finding the balance between the demands of growth, the requirements of functioning natural systems, and our need for productive agricultural and forestry lands. The decisions we make today will affect available resources, the sense of place that we value, and the legacy we leave to following generations. Through regulatory and non-regulatory efforts, the County is continually striving to minimize environmental impacts to preserve the clean air and water, forested mountains, and thriving economy we all enjoy. Some human activities in our sensitive natural environment need to be avoided, while others can be mitigated. The County is committed to working together with the citizens of this region for the common good of all.

Snohomish County has created environmental policies and regulations and implemented land use law to protect natural resources for more than three decades. In the early 1970s the County adopted the Shoreline Management Master Program and began utilizing the State Environmental Policy Act regulations to protect environmentally sensitive areas. In the 1980s the storm and surface water utility was established to protect water quality and quantity and the Aquatic Resource Protection Program was initiated, and then repealed by citizen referendum shortly after adoption in 1990. Also in the 1990s, a groundwater advisory committee was formed and the Stillaguamish Clean Water District was established. Recognizing the need for further protection of limited natural resources, Snohomish County adopted its first Critical Area Regulations (CAR) in 1995.

Critical Area Regulations (CAR) that designate and protect environmentally critical areas' functions and values are required under Washington State's Growth Management Act (GMA), which was enacted in 1990. The GMA defines critical areas as wetlands, critical aquifer recharge areas, fish and wildlife habitat areas, frequently flooded areas, and geologically hazardous areas. The County is currently reviewing and updating CARs to include Best Available Science (BAS), as required by the GMA.

Integrating new scientific understanding with current regulations, incentives, and educational and stewardship efforts provides a cohesive program of environmental protection. There are trade-offs; each part of the strategy has pros and cons, but as an interconnected plan the pieces work together to achieve the goal of adequately protecting our natural resources while meeting the needs of the community of Snohomish County.

Purpose of Update

Protecting the environment is protecting that which sustains us. Environmental safeguards ensure water quality and availability, our capacity to grow food, and abundant marine resources to harvest. The Legislature's requirement to include Best Available Science (BAS) is an important step in meeting the challenges of a growing population's impacts to the natural environment.

This update will also reform regulations by improving predictability and timeliness of project permitting decisions. Local governments' understanding of where on the landscape critical areas occur, how they naturally function, and how best to regulate land uses that may impact critical areas natural processes is important in ensuring that zoning and project permit decisions can be made with minimal need to complete expensive environmental review and new studies at the permit level. In addition, alternatives must be available where application of regulations makes property use impractical. Good upfront planning and the adoption of scientifically defensible development standards should lead to better protection of critical areas and quicker permit decisions.

The Role of Best Available Science

All of the five critical areas provide significant ecological functions and value. Frequently flooded areas and geologically hazardous areas also pose potential risk of endangering humans and property and causing economic loss. Science provides the foundation for credible decision-making, and it plays a central role in identifying critical areas and recommending strategies to protect their functions and values and ensure human safety. With a better understanding of environmental risks to people and ecosystems, local government can develop innovative solutions to environmental problems before they reach a critical level. Using best available science will help jurisdictions to plan development near critical areas appropriately to minimize loss of life, ecological value, and economic assets.

This document synthesizes the BAS for critical areas in Snohomish County. The science is being utilized to guide revisions to County policy and development regulations. In addition to the science, the County will also review the *Environmental Impact Statement of the Proposed Critical Area Regulations*, and public input to ensure that community values are incorporated in the updated regulations.

The County followed "The Minimum Guidelines to Classify Agriculture, Forest Mineral Lands and Critical Areas" to outline the primary topics covered in this report. Several key documents were drawn upon, including: Pentec Environmental's report *Review Draft, Appendix B, Use of Best Available Science in Critical Area Protection in Snohomish County, June 9, 2004*; *Best Available Science, Volume 1, A Review of Science Literature, King County Executive Report, February 2004*; and scientific information gathered through an extensive literature review by Snohomish County engineers and scientists. The wetlands chapter is adopted in its entirety from the Washington State Department of Ecology's *Freshwater Wetlands in Washington State, Volume 1: A synthesis of the science*.

Identifying Best Available Science

The science in this document was gathered following the BAS rules contained in WAC 365-195-900 thru 925. These rules define Best Available Science as having the characteristics of a valid scientific process. These characteristics are outlined in WAC 365-195-905 and include the following:

- Peer review by other persons who are qualified scientific experts in that scientific discipline. Publication in a professionally refereed scientific journal is usually appropriate; this does not include newspaper articles or popular journals.
- Followed a replicable method. The methods are standardized in the pertinent scientific discipline or, if not, the methods have been appropriately peer-reviewed to assure their reliability and validity.
- Reaches logical conclusions and reasonable inferences. The conclusions presented are based on reasonable assumptions supported by other studies and consistent with the general theory underlying the assumptions. The conclusions are logically and reasonably derived from the assumptions and supported by the data presented. Any gaps in information and inconsistencies with other pertinent scientific information are adequately explained.
- Uses appropriate statistical or quantitative methods for analysis.
- Appropriately frames conclusions with respect to the prevailing body of pertinent scientific knowledge, and adequately references assumptions, analytical techniques, and conclusions with citations to relevant, credible literature and other pertinent existing information.

Common sources of scientific information include:

- Research data collected and analyzed as part of a controlled experiment (or other appropriate methodology) to test a specific hypothesis.
- Monitoring data collected periodically over time to determine a resource trend or evaluate a management program.
- Inventory data collected from an entire population or population segment (e.g., individuals in a plant or animal species) or an entire ecosystem or ecosystem segment (e.g., the species in a particular wetland).
- Survey data collected from a statistical sample from a population or ecosystem.
- Mathematical or symbolic simulation or representation of a natural system. Models generally are used to understand and explain occurrences that cannot be directly observed.
- Assessment. Inspection and evaluation of site-specific information by a qualified scientific expert. An assessment may or may not involve collection of new data.
- Synthesis. A comprehensive review and explanation of pertinent literature and other relevant existing knowledge by a qualified scientific expert.
- Expert Opinion. Statement of a qualified scientific expert based on his or her best professional judgment and experience in the pertinent scientific discipline. The opinion may or may not be based on site-specific information.

Local governments must identify, collect, and assess the available scientific information relating to the protection of critical areas within their jurisdiction, and then determine which of that science constitutes the "best available science." Local governments may accept or solicit scientific information from state and federal agencies, universities, tribes, subject matter experts, and others, but the burden ultimately is on the local government to determine whether the scientific information assembled constitutes the best available science.

Summary of Best Available Science Rules

WAC 365-195-900 explains the background, purpose, and statutory context of the best available science rules. These rules are intended to assist counties and cities in identifying and including the best available science in newly adopted policies and regulations and in demonstrating they have met their statutory obligations under RCW 36.70A.172(1).

Counties and cities must include the best available science when developing policies and development regulations to protect the functions and values of critical areas and must give "special consideration" to conservation or protection measures necessary to preserve or enhance anadromous fisheries. RCW 36.70A.172(1).

The inclusion of the best available science in the development of critical areas policies and regulations is especially important to salmon recovery efforts, and to other decision-making affecting threatened or endangered species.

WAC 365-195-905 explains the criteria for determining which information is the best available science. This section provides assessment criteria to assist counties and cities in determining whether information obtained during development of critical areas policies and regulations constitutes the best available science.

Counties and cities may use information that local, state or federal natural resource agencies have determined represents the best available science. The responsibility for including the best available science in the development and implementation of critical areas policies or regulations rests with the legislative authority of the County or city. However, when feasible, counties and cities should consult with a qualified scientific expert or team of qualified scientific experts to identify scientific information, determine the best available science, and assess its applicability to the relevant critical areas. The scientific expert or experts may rely on their professional judgment based on experience and training, but they should use the criteria set out in WAC 365-195-900 through 365-195-925 and any technical guidance provided by the department.

WAC 365-195-910 offers recommendations as to where local governments can obtain the best available science. A county or city may compile scientific information through consultation with state and federal natural resources agencies and tribes, or through its own efforts, with or without the assistance of qualified experts, and through state agency review and the Growth Management Act's required public participation process.

WAC 365-195-915 provides criteria for demonstrating that the best available science has been included in the development of critical areas policies and regulations. Counties and cities should address the specific policies and development regulations adopted to protect the functions and values of the critical areas at issue; the relevant sources of best available scientific information included in the decision-making; any nonscientific information – including legal, social, cultural, economic, and political information – used as a basis for critical area policies and regulations that depart from recommendations derived from the best available science. A county or city departing from science-based recommendations should identify the information in the record that supports its decision to depart from science-based recommendations; explain its rationale for departing from science-based recommendations; and identify potential risks to the functions and values of the critical area or areas at issue and any additional measures chosen to limit such risks.

WAC 365-195-920 explains what to do if a county or city cannot find enough scientific information applicable to its critical areas. Where there is an absence of valid scientific information or incomplete scientific information relating to a county's or city's critical areas, leading to uncertainty about which development and land uses could lead to harm of critical areas or uncertainty about the risk to critical area function of permitting development, counties and cities should use a "precautionary or a no risk approach," in which development and land use activities are strictly limited until the uncertainty is sufficiently resolved.

WAC 365-195-925 outlines the criteria for demonstrating that “special consideration” has been given to conservation or protection measures necessary to preserve or enhance anadromous fisheries. To demonstrate compliance with RCW 36.70A.172(1), a county or city adopting policies and development regulations to protect critical areas should include in the record evidence that it has given "special consideration" to conservation or protection measures necessary to preserve or enhance anadromous fisheries.

Conservation or protection measures necessary to preserve or enhance anadromous fisheries include measures that protect habitat important for all life stages of anadromous fish, including, but not limited to, spawning and incubation, juvenile rearing and adult residence, juvenile migration downstream to the sea, and adult migration upstream to spawning areas. Special consideration should be given to habitat protection measures based on the best available science relevant to stream flows, water quality and temperature, spawning substrates, instream structural diversity, migratory access, estuary and nearshore marine habitat quality, and the maintenance of salmon prey species. Conservation or protection measures can include the adoption of interim actions and long-term strategies to protect and enhance fisheries resources.

Summary of the Five Critical Areas Chapters

Chapter 1 - Critical aquifer recharge areas

Critical Aquifer Recharge Areas are geographic areas where water enters aquifers used for drinking water and may be vulnerable to contamination. Aquifers are areas where groundwater, water beneath the earth’s surface, has collected in an appreciable quantity and can be economically withdrawn by wells. An aquifer recharge area occurs where water (e.g. precipitation, and irrigation, septage, and stormwater runoff) can seep into permeable soil or rock in sufficient volumes to replenish an aquifer. Water may descend vertically and collect in layers of rock, or it may flow underground at a downward slope for several miles before accumulating in an aquifer, discharging into a stream, or surfacing as a spring.

Delineating critical aquifer recharge areas is based on the physical properties of the aquifer. Snohomish County's critical aquifer recharge areas are delineated by combining a determination of aquifer sensitivity with a determination of aquifer vulnerability. The physical properties of the unsaturated and saturates zones determine the sensitivity of an aquifer to human activity. In Snohomish County, groundwater recharge occurs over approximately 70-80 percent of the land surface. What people do on the land and within the geographic location that an aquifer occurs can directly impact the water quality of drinking water for thousands of residents. Snohomish County has identified and mapped the areas that are the most sensitive to human activities and groundwater contamination. The result is a map showing areas with low, moderate, and high sensitivities. For example, areas underlain by impermeable material such as glacial till or bedrock and where the water table is deep (50 feet or more below the ground surface) are considered to have a low sensitivity. Areas underlain by permeable alluvium or loose glacial outwash and where the water table is near the surface (as little as 2 feet below the ground surface) are considered to have a high sensitivity.

Developing an effective map of aquifer sensitivity is difficult because the propensities of the aquifer system, the depth to groundwater, and the direction of groundwater are not precisely known for the entire County. There are many methods available, some more costly than others, and the science in this field is evolving. The Critical Area Recharge Map for Snohomish County was developed using widely accepted methods and is flexible enough to be updated as new data are collected and the methodology is refined. Increased access to water level data will refine our knowledge of where groundwater occurs. Eventually, statistical methods, such as logistical regression or deterministic groundwater flow models, will be employed to predict the actual sensitivity of an aquifer to contamination.

There are approximately 15,500 reported domestic water-wells in Snohomish County. The geographic area surrounding a single well serving multiple connections is known as a wellhead protection area. There are approximately 375 wells in the County that serve 2-14 connections and are protected by an arbitrarily assigned 600-foot fixed radius buffer or wellhead protection area. There are approximately 290 wells in the County that serve 15 or more connections. These wells are protected by a buffer that is defined by the distance water will travel in the saturated zone in 10-years. These wellhead protection areas can be a fixed circular radius or an irregular shape. Even with protection, groundwater quality cannot be assured. Natural minerals in the ground are often found in the groundwater tapped by private wells that exceeds the current maximum contaminant levels set by the Department of Ecology.

Limited protection to drinking water supplies is provided by the sole source aquifer (SSA) program. This program is not a comprehensive groundwater protection program; it provides protection from federally funded projects that have the potential to contaminate. Many sensitive aquifers remain undesignated simply because no one has filed a petition on their behalf, and drinking water consumption patterns above the aquifer may not qualify it for SSA status. Snohomish County currently has two designated sole source aquifers – the Cross Valley Aquifer, located in the Clearview-Maltby area; and the Newberg Area Aquifer, located east and south of the Pilchuck River.

Primary issues of concern in Snohomish County are land uses that produce high levels of non-point source pollution, such as urban run-off, agricultural run-off, or septic disposal, and land-uses associated with point source pollutants, such as industrial facilities. A USGS study in 1997 found elevated concentrations of nitrate and ammonia in isolated areas due to agricultural activities and septic systems. The County's water quality staff have identified bacterial levels exceeding state standards in several streams due to potential septic problems.

The quantity of groundwater is also a concern. If precipitation is not allowed to seep into the ground, because it runs off impervious surfaces or is no longer stored in wetlands, the amount of water available to recharge an aquifer will decrease, lowering the water table and decreasing discharge to streams. Also, if significant amounts of water are removed from a basin, water tables can decrease. There are many competing uses for groundwater and demand is increasing.

Mapping Critical Aquifer Recharge Areas provides the general framework for a groundwater quality and quantity protection policy. The County has designated four classes of Critical Aquifer Recharge Areas. Snohomish County's Critical Aquifer Recharge Area Map has identified areas of low, medium, and high sensitivity to groundwater contamination based on the physical properties of the aquifer system and then overlaid groundwater supplies that are vulnerable to contamination to identify areas that require protection because of their critical aquifer recharge function.

Chapter 2 - Frequently flooded areas

Snohomish County regulates flood hazard areas to protect against injury, loss of life, property damage and financial loss due to flooding. Flood hazards include riverine inundation, coastal flooding, tsunamis, and failure of flood control structures. The science in this chapter provides a delineation of the extent of the hazard, an assessment of the probability of the flood hazard occurring, and an estimate of the potential damages resulting from flooding.

Riverine flooding is a natural process that occurs when floodwaters rise above the natural containment levels in rivers and streams following intense rainfall and/or snowmelt. While flooding exacerbates the risk of damage to people and properties, a naturally functioning floodplain provides storage and conveyance of flood waters, the recharging of groundwater, the maintenance of water quality, and habitat for fish and wildlife.

The major rivers in Snohomish County, the Skykomish, Snohomish, Snoqualmie, Stillaguamish, and the Sauk, all descend from the crest of the Cascade Mountains to Puget Sound and are heavily influenced by snow and rain patterns in the mountains. In the western portions of the County, there are numerous small streams with moderate to high amounts of watershed development where flooding can be heavily influenced by stormwater runoff from urbanization. When development occurs on or near floodplains, people and property become exposed to increased flood hazards. Future flood risk is generally increasing due to development and climate change. The County has considered predicted future flows in identifying restoration opportunities.

The Federal Emergency Management Act establishes standards for mapping floodplain areas and setting development guidelines within those areas. The current maps for most large rivers in Snohomish County were completed in the early 1980s and are being updated within the next year. The current floodplain storage model does not take into account flood fringe development. Future flood risk is known to be generally increasing due to both development and climate change. In the smaller watersheds of western Snohomish County, where the majority of development is taking place, County engineers have predicted increased future flows resulting from extensive development in the watersheds and have identified capital improvement programs to mitigate flood hazards.

Coastal flooding in Snohomish County is a less frequent flood hazard and is generally caused by intense winter storm systems arriving from the Pacific Ocean. Rising global sea levels are predicted to contribute significantly to coastal inundation. A more severe potential hazard is failure of levees during floods. This can lead to localized erosion and flooding hazards. Breaches have occurred in every large flood in recent decades.

The threat of a tsunami is also a potential flood hazard. Earthquakes, landslides, and volcanic eruptions can generate tsunamis. Detailed tsunami modeling of the Elliot Bay area in Seattle has shown a tsunami of around 6m results in wave run-up of up to 10m against steep bluffs, and inundation of flat low lying areas up to 1 mile inland. Tsunami hazard maps will be available as detailed damage modeling is completed for Snohomish County. Low-lying coastal areas and river deltas are at risk from tsunamis.

Chapter 3 - Fish and wildlife habitat conservation areas

Washington state law requires the conservation of fish and wildlife habitat to maintain species within their natural geographic distribution so that isolated subpopulations are not created. This chapter focuses on the functions and values of aquatic areas and wildlife habitat, processes that form and sustain these areas and associated species, and the effects of land development and stormwater on critical areas.

The most basic functions of an aquatic area are the storage, purification, and transport of water. Aquatic areas also function as habitat for a large number of plants and animals. These habitats and the species that use them are integrated parts of an aquatic ecosystem that has developed, and continues to develop, due to a myriad of climatic, geologic, and plant and animal interactions. Human uses and development of land and water often affects this ecosystem in profound ways, ultimately affecting the type and abundance of species that exist.

Salmonids are of particular interest in Snohomish County, as well as throughout the Pacific Northwest, because of their cultural, social, political, legal and economic importance. Regionally, among all counties, Snohomish County is host to the greatest number of independent populations of threatened Chinook salmon.

Salmonids are also important ecologically, as they are the region's most diverse family of freshwater and anadromous fishes. They bring nutrients from highly productive marine areas to otherwise nutrient-poor freshwater streams and riparian areas when they return to spawn. Hundreds of aquatic invertebrates, birds, mammals, amphibians, and reptiles are predators or scavengers of salmon. In some cases, they spawn in sufficient numbers that their digging action modifies the shape of streams and in the process cleans sands and silts from stream substrates. For these reasons, salmonids are considered keystone species and are a commonly used benchmark for setting protection standards and assessing the effectiveness of aquatic habitat protection and restoration measures.

Studies have shown that fish species diversity declines with increasing levels of urban development. When a watershed reaches approximately 10 percent effective impervious area, demonstrable loss of aquatic system function occurs. Numerous studies have shown that development within a watershed can also be directly linked to physical degradation of aquatic areas and quality of habitat. In the Snohomish River basin, near continuous diking, riparian clearing, and wood removal has reduced the marsh areas by 83% and the historic blind tidal slough area by 75%. There is no known suitable, long-term substitute for healthy riparian forests and research indicates that buffer protection, land use controls, and stormwater management programs in combination may form the best approach. Use of proper agricultural Best Management Practices can also help reduce the impacts of agricultural activities.

The changes in landscape that occur with increased human population typically result in increases in intensity and quantity of stormwater flows in rivers and streams. These changes can exacerbate channel migration, drought conditions, and water quality. Natural vegetation and pervious surfaces lessen the water flow, allowing infiltration and storage of water. Indexes of biotic integrity have shown a direct correlation between watershed conditions and measures of hydrologic alterations. Surface runoff in forested watersheds is estimated between 12% and 30%, while in developed watersheds it is estimated between 44% and 48%. The key to attaining effective aquatic area protection against landscape level changes is maximizing native forest cover (including continuity of riparian areas along streams and wetlands) and minimizing impervious surfaces.

Buffers are frequently recommended to protect critical aquatic areas by providing shade and temperature regulation, flood conveyance, water quality protection and pollutant removal, nutrient cycling, sediment transport, bank stabilization, woody debris recruitment, wildlife habitat and microclimate control. A variety of technical reports summarize the scientific literature on buffer functions and make recommendations for buffer widths. These range from 35 to 1000 feet, depending on specific species, habitat type, and land use. Variable buffer widths can potentially allow for greater flexibility in achieving ecological goals while minimizing loss of useable land.

Terrestrial species and habitat can be protected through the use of clearly identified ecological reserves and by enhancing the quality of existing habitat and providing protection for ecological functions, ecological composition, and adequate habitat structure. Generally, large patches of a given habitat type are more valuable than small patches. Key habitats include old-growth and mature forests, riparian areas, and wetlands. Maintaining or creating wildlife corridors is valuable in facilitating movement of animals between essential breeding, feeding, and roosting habitat and in minimizing negative attributes (e.g., reduced numbers, inbreeding, greater vulnerability to local extinction) of isolated populations. Buffers are also especially important when human activity may affect the area.

Restoration of wildlife habitat is also valuable for stemming and reversing the loss of wildlife. Strategic land use planning which examines temporal patterns of human demography and dispersal as well as the spatial distribution of habitat can significantly contribute to the persistence and recovery of wildlife populations.

Chapter 4 - Geologically hazardous areas

Geologically hazardous areas include areas associated with seismic and volcanic activity, abandoned mines, erosion, and landslide areas. These areas are primarily identified and regulated for human safety, although there are guidelines for landslide and erosion hazards that can affect habitat.

There are many areas of Snohomish County that are seismically active. Building codes that require earthquake resistant design and construction have been implemented in Snohomish County since 1962. The standards, formulas and methods to calculate these forces are frequently updated as new knowledge is acquired. The science at this point is not able to predict locale and strength of earthquake events, but can reduce the impact of seismic events through structure design that requires earthquake resistant construction, and analysis of site periodicity.

Earthquakes can also generate landslides, tsunamis, and seiches. Landslide prone areas are Deer Creek on the Stillaguamish, the Lowell Larimer Bluffs, portions of Arlington Heights, Possession Lane, Picnic Point, Edmonds-Meadowdale Area, Woodway and Mukilteo bluff communities and some of the bluffs on Hat Island. Tsunami hazards were discussed above in the flood hazard section. Earthquakes may induce seiches (standing waves, in lakes, bays, and rivers), but they are more commonly caused by wind-driven currents or tides.

Landslide processes are well understood, though the site-specific elements of each event are highly variable. Landslide Hazard Areas are areas of the landscape that are at high risk of future soil movement or slope failure or that presently exhibit downslope movement of soil and/or rocks and that are separated from the underlying stationary part of the slope by a definite plane of separation or geologic contact. Landslides are a significant problem in Snohomish County, with several landslides occurring every year during the rainy season, generally from November through April. They are generally triggered by storms creating excess ground water. Future earthquakes in Washington are expected to generate more landslides and greater losses than reported for past earthquakes because economic growth continues to exert pressure to develop in or near landslide-prone areas, such as view bluff property; increased erosion and consequent downcutting caused by urban runoff has locally reduced slope stability; and new or previously unidentified landslides damage structures that were built in unstable areas before critical area regulations existed.

The degree of development in a basin or subbasin area greatly affects the erosion potential. Urban developments can result in the replacement of permeable natural surfaces like forest canopy and brush with impermeable surfaces. This causes stormwater runoff to increase significantly, unless the natural aquifer recharge areas and wetland systems are preserved, and it causes the peak rate of runoff to increase. Both effects result in a significant increase in the erosion potential within the basin or subbasin. High velocity water flow can create bank erosion and result in movement or shifting of the channel, called channel migration. Sediment in stream systems caused by erosion hazards can be hazardous to habitat and human structures, but can also be very important to the overall function and health of a stream system. Natural erosion and landsliding processes provide the sand, gravel, cobbles, and boulders that streams need to remain productive with respect to fish and other aquatic organisms. Best Management Practices (BMPs) can be employed to limit erosion and sedimentation during construction so that excess sediment runoff into stream systems is limited.

In Snohomish County, widespread damage from a volcano is most likely to come from an eruption on Glacier Peak. Volcanic hazards comprise a variety of phenomena that occur in zones around an active volcano. In the Pacific Northwest, the presence of a series of subduction zones and stratovolcanos presents a unique and very dangerous hazard to local populations and infrastructure. As population in Snohomish County increases, encroachment into areas that may be subject to volcanic hazards increases. Regulatory restraints or sensible siting of homes adjacent to potential lahar areas may help save lives during the next eruption on Glacier Peak. A lahar is a mixture of water, ice, and sediment that is generated during and sometimes after an eruption. In Snohomish County the community of Darrington is at risk from a lahar event and associated landslide/mudflow/flooding event from the Sauk River and Stillaguamish River system.

Abandoned mine hazard areas are recorded and mapped by the Washington State Department of Natural Resources, Division of Geology and Earth Resources. Not all former mine sites will appear on the available maps, either because the mines were worked prior to 1900 or because they were small and unregistered by the State. Snohomish County has a long history of active mining of gravel and mineral resources lands. Some of the better known mining areas are around Monte Cristo, Granite Falls and in the vicinity of the Town of Index. Literature review indicates that these hazard areas should have protection boundaries applied to them that have the same effect and function as buffers.

These five geologic hazard areas pose potential physical hazards to life, limb, property, or the environment. Site-specific review of specific soil types, slope gradients, climatic conditions, and many other factors that dictate the degree of hazard associated with any particular site is the most effective method to accurately evaluate the potential for development of a hazardous condition. Certain types of protection areas of varying, but conservative widths may be substituted for site-specific evaluation. Current science-based and fully implemented construction standards and Best Management Practices (BMPs) can be used to ameliorate the potential hazards.

Chapter 5 - Wetlands

This chapter discusses how environmental factors control the functions of wetlands across the landscape and at individual sites, how freshwater wetlands are classified according to these controls, and what functions are performed by different classes of wetlands in the state. It also addresses how human activities and land uses affect the environmental factors that control wetland functions, how wetlands are protected and managed using common tools such as buffers and compensatory mitigation, and how cumulative effects result from the current use of these tools.

Wetland functions are the physical, biological, chemical, and geologic interactions among different components of the environment that occur within a wetland. Functions fall into three broad categories: biogeochemical (water quality), hydrologic (water flow and aquifer recharge), and interactions that maintain food webs and habitats for plants and animals. The major controls of function are climate; geomorphology and soils; the source and quantity of water; the movement of water, nutrients, other chemicals, and sediments; energy in the form of sunlight; and biological interactions. Functions, in turn, can then modify the processes and structure of wetlands.

The capacity of a wetland to store surface water affects its ability to reduce peak flows, as does the amount of flow from the upper watershed that enters the wetland and the amount of woody vegetation present. Reducing peak flows helps to decrease flooding, as well as downstream erosion. Wildlife species can be wetland dependent or wetland users. Characteristics that are important for many species include vegetation structure, water depth, water level fluctuation, buffers, snags, and connections to other habitats and wetlands in the landscape. Wetlands have high productivity of plant material. Decomposed plant material can be exported downstream, providing food for insects, fish, and other organisms in the food web.

The most important factors that control functions at an individual site may occur somewhere else in the landscape. Information about factors that control functions at the larger scale is still evolving. The importance of the environmental factors that occur at the larger, landscape scale, however, should not be minimized for lack of information. Individual wetlands function to a large degree through interaction with the adjacent portions of the landscape and with other wetlands. For example, wetlands whose principal source of water is groundwater depend on that water infiltrating in the surrounding uplands. If these uplands are paved, clear-cut, or farmed, the amount of water recharge is significantly reduced and the wetland may dry up or become smaller.

Disturbances that impact wetlands the most include direct changes to the physical structure of wetlands from filling, vegetation removal, tilling of soils, and compaction of soils; changes in the amount of water in wetlands and fluctuation of water levels; changes in the amount of sediment, nutrients, toxic contaminants, and acidity; increasing concentration of salts; and increasing fragmentation of habitat.

Wetland buffers are a critical tool for protecting wetland functions. Widths of buffers should be related to the wetland functions that need protection, the land-use activities from which the wetland is being buffered, and the characteristics of the buffer itself. Wetland compensatory mitigation projects have an intermediate level of success. This chapter provides numerous suggestions on improving mitigation efforts.

Chapter 1 – Critical Aquifer Recharge Areas

Introduction

Critical Aquifer Recharge Areas (CARAs) are the geographic areas that have a "critical recharging effect on aquifers used for potable water" (RCW 36.70A.030(5)). This chapter presents the best available science on protecting critical aquifer recharge areas. It defines aquifer recharge areas and describes the best available methods for prioritizing these areas. It also discusses Snohomish County's method for determining aquifer recharge areas and the existing concerns and issues specific to the County.

Definition of Aquifer Recharge Areas

Groundwater is all water beneath the earth's surface. It flows and seeps from where the water table is highest to where it is lowest and often collects in layers of sediment or rock. An aquifer, for the purposes of this chapter, is a reservoir of an appreciable amount of groundwater. An aquifer is defined in Snohomish County Code (SCC 30.91A.260) as "a geologic formation, group of formations, or part of a formation capable of yielding a significant amount of groundwater to wells or springs."

As rain falls, snow melts, and farms are irrigated, the water seeps into the ground and recharges aquifers. An aquifer recharge area occurs where there is permeable soil or rock; this may occupy only a very small area or extend over many square miles. Groundwater may descend vertically directly into an aquifer, or may flow downslope underground for several miles before accumulating in an aquifer, discharging into a stream, or surfacing as a spring. Valley aquifers may also receive recharge from hillside runoff or streams that flow down from hillsides. Recharge areas serve to replenish the groundwater aquifer supplies, but also allow for transportation of contaminants into an aquifer. The quality of groundwater in an aquifer is inextricably linked to its recharge area.

In principle, any groundwater is sensitive to human activity and practically all groundwater comes as recharge at the land surface (Harter and Walker 2001). Typically, groundwater recharge occurs over approximately 70-80 percent of the land surface (Dingman 2002). If similar distributions hold for Snohomish County, the majority of the County is a groundwater recharge area. For this reason, Snohomish County started by delineating the areas sensitive to contamination based on the physical properties of the aquifer systems found throughout the entire Ground Water Management Area (GWMA), using the best available science described in this chapter. In addition to sensitivity, areas with significant groundwater supplies were also plotted. A map showing the designated GWMA and associated CARAs is available for viewing or purchase at Snohomish County Planning and Development Services.

A critical aquifer supplies the water needs for a community. CARAs are the geographic areas "where an aquifer that is a source of drinking water is sensitive to contamination that would affect the potability of the water" (WAC 365-190-030). All groundwater is potentially sensitive to contamination. However, existing data on groundwater contamination shows that problems vary spatially and not all regions are equally sensitive (Merchant 1994). The same is true of Snohomish County (Thomas et al. 1997).

The risk of groundwater contamination typically depends on the physical properties of the aquifer system, such as the depth to groundwater, and soil and underlying ground characteristics regardless of the presence or absence of potential contaminants. The risk of groundwater contamination is also a function of what potential contaminants are placed above an aquifer by a given land use. Deep aquifers are less sensitive to contamination than are shallow aquifers as it is more likely that a contaminant will breakdown or disburse prior to reaching the aquifer. Land use activities such as the handling and storage, chemical properties, and amount of potential contaminants used can contribute to how easily potential contaminants might reach groundwater. Permeability of the soils and underlying ground also contribute to contamination sensitivity. Permeable soil can allow contaminants to easily flow into aquifers. Less permeable soil, however, can act as a natural filter to screen out many substances that mix with the water. In Snohomish County, relatively impermeable till soils predominate. These impermeable soils slow that rate of groundwater infiltration and that allows some contaminates to breakdown or diffuse before reaching an aquifer. The protection of impermeable soils is not absolute, since the accumulation of large volumes of contaminants can, over time, reach the aquifer.

Effective protection strategies for groundwater need to be targeted at the most critical areas. The Washington State Department of Ecology established the following guidance for groundwater protection:

1. All groundwater is sensitive to contamination; however, hydrogeologic conditions in some areas create a greater potential to convey contamination from points of recharge (locations where groundwater is replenished) to points of use. To protect groundwater in critical or sensitive areas, it is necessary to first prioritize the most critical areas using technically sound, but politically and economically realistic methodologies.

2. A CARA delineation is based upon the known or suspected sensitivity of aquifer(s) within a designated area. Groundwater sensitivity (relative ease with which contaminants will reach the aquifer) and groundwater vulnerability (relative ease with which contaminants will reach the aquifer for a given set of land-use practices) are combined to determine an aquifer's overall sensitivity. The vulnerability determination is based upon known and inferred conditions developed from limited field data. In some cases, it is difficult to determine known conditions. In these situations it is necessary to adopt a conservative approach as it applies to contaminant migration. In this case, it is assumed that contaminants will not be either retarded or degraded as they pass from the surface to the underlying aquifer(s). Using this approach will entail basing initial critical aquifer recharge areas on susceptibility. As additional data becomes available delineation is likely to be modified and based on a combination of aquifer susceptibility and contaminant behavior. Previous geologic and/or hydrogeologic characterizations contain information valuable to determining where a CARA may exist. All readily available information pertaining to designations of aquifer sensitivity or aquifer vulnerability should be used in order to complete an initial determination.

3. Previous water quality information, collected as part of a study or survey, which indicates degraded groundwater or negative changes in groundwater quality, should be considered as an indication of how sensitive an aquifer system is to contamination.

4. To the greatest extent possible, ordinances resulting from the requirements of the Growth Management Act should address the requirements of the Water Pollution Control Act, the Water Resource Act of 1971, Groundwater Quality Standards, and Washington State's antidegradation policy.

For clarification, "aquifer sensitivity" means the ease with which contaminants can move from the land surface to the aquifer, based solely on the types of surface and subsurface materials in the area. Sensitivity usually defines the rate at which a contaminant will reach an aquifer unimpeded by chemical interactions with the media within the unsaturated (or vadose) zone. "Vulnerability" is the combined effect of sensitivity to contamination and the presence of potential contaminants.

Best Available Methods for Prioritizing Aquifer Recharge Areas

Groundwater sensitivity or vulnerability assessments are a process where all relevant and available groundwater related information is assembled to produce a map that distinguishes areas of greater vulnerability from areas of lesser vulnerability. Hence, vulnerability mapping and vulnerability assessments are sometimes referred to interchangeably. The three most commonly used methods developing vulnerability assessments are: (1) index-and-overlay methods, (2) process-based computer simulations, and (3) statistical analyses (Focazio et al. 2002).

Index-and-overlay methods. These methods compile information on the most relevant factors affecting aquifer sensitivity such as depth to groundwater, land use, and soil type. The pre-determined variables are then combined to produce an index, rank, or zones of "sensitivity." The scoring system is based on expert opinion rather than processes, and therefore, is inherently subjective. Index and overlay methods result in a simple map of sensitivity that subjectively categorizes an area from low to high.

The advantage to this method is that index and overlay maps can be easily incorporated into management and policy decision making. They are designed to use readily available information from local, state, or federal government agencies, and work particularly well with geographic information systems (GIS), since they allow for overlaying multiple maps showing soil properties, depth to water table, and recharge.

In the United States, the most widely-used sensitivity assessment method in this category is the "DRASTIC" index (Aller et al.1987). This index uses the weighted average of 7 values corresponding to 7 hydrogeologic parameters. These parameters and the weights assigned to them are summarized in the following table:

Table 1.0 DRASTIC Index

	Weight
Depth to the water table	5
Net Recharge	4
Aquifer material	3
Soil type	2
Topography	1
Impact of the vadose zone	5
Hydraulic Conductivity	3

Each parameter used in the DRASTIC index has a predetermined, fixed, relative weight that reflects its relative importance to susceptibility. The most significant factors have weights of 5; the least significant a weight of 1.

The DRASTIC sensitivity index is calculated by first assigning a value between 1 and 10 for each parameter, depending upon local conditions. High values correspond to high sensitivity. The attributed values are obtained from tables, which give the correspondence between local hydrogeologic characteristics and the parameter value. Next, the local index of sensitivity is computed by multiplying the value attributed to each parameter by its relative weight, and adding up all seven products. The minimum value of the DRASTIC index is therefore 23 and the maximum value is 226. Such extreme values are very rare, the most common values being within the range 50 to 200.

The DRASTIC approach for ranking groundwater sensitivity has been widely used both in North America (Fagnan et al. 1998; Navulur and Engel 1998; Ducci 1999; Stark et al. 1999; Fritch et al. 2000) and around the world, including China, India, Portugal, South Africa, and Algeria (Menani 2001; Dai 2001; Shahid 2000; Lobo-Ferreira et al. 1997; Lynch et al. 1993). Subsets of the DRASTIC parameters and variations on these parameters have also been extensively used. Many jurisdictions in the US, England, Wales, Ireland, and Australia all use subsets (Burgess and Fletcher 1998; Ireland DOE 2001; Merchant 1994).

Snohomish County has focused on the rate of groundwater recharge and depth to groundwater as the two most significant parameters. Recent findings, however, have shown that geologic material and depth to groundwater may provide more useful information on aquifer sensitivity in the Pacific Northwest region (Troost et al. 2005). Using this technique, recharge is given less weight, since there is sufficient recharge throughout this region to carry a contaminant to the water table. Snohomish County is currently evaluating new methodologies and will update the GWMA/CARA map as it is refined.

Process-based computer simulations. Otherwise known as computer models, these simulations can interpret complex physical and chemical processes at a very detailed level to produce an assessment of an aquifer systems true sensitivity to groundwater contamination. These models can be used to develop a full vulnerability assessment by coupling the model results with an analysis of contaminants available for a given land use. Computer models allow for geologic and hydrogeologic three-dimensional resolutions because they can incorporate depth. Modeling enables the user to simulate–the flow and transport patterns within the vadose zone or in an actual aquifer. Examples of unsaturated zone models are PRZM, LEACH, HYDRUS, and MODFLOW, with the latter being an especially popular groundwater model.

Process based computer simulations have proven useful in assessing sensitivity when the following conditions apply (Harter and Walker 2001):

- a more localized analysis of specific vulnerability to particular land uses (particular contaminants) is required and sufficient data are available or can be collected to prepare the computer model;
- a number of "what-if" scenarios involving complex processes need to be evaluated for making important land use planning decisions.

However, models are not commonly used for sensitivity or vulnerability assessments because of the considerable data requirements and expertise required to run and interpret the results. It is not a preferred choice when economic resources are limited.

Statistical methods. Statistical methods quantify the risks of groundwater pollution by making relationships between observed contamination, observed environmental conditions, and potential sources of contamination. Once a relationship has been developed, it is used to predict the potential risk of contamination in uncontaminated areas, and in principal, the higher the contamination risk, the higher the sensitivity. This allows the risk to be quantified. Large quantities of high quality data are required to develop the predictive statistical relationships, and once the relationships are established, it can only be applied to regions that have similar environmental conditions and contaminants.

In recent studies (Tesoriero and Voss 1997; Erwin and Tesoriero 1997; Focazio et al. 2002), the USGS has been successful in using a type of statistical method called logistic regression in assessing groundwater sensitivity and groundwater vulnerability in Washington and Colorado to explain the occurrence of high nitrate or pesticides. The logistic regression approach calculates actual probability of detections instead of assigning subjective categories such as "high," "moderate," and "low" sensitivity. The process of weighting or ranking the variables such as geology and soils is automatically evaluated by logistic regression and therefore does not depend on weighting factors based on qualitative criteria and professional judgment, like the DRASTIC approach (Williamson 2004). However, like most statistical analyses, this method requires groundwater quality data on specific contaminants, like nitrate or pesticides, and usually occurs *after* contamination has already occurred.

The sensitivity maps produced by the methods described above are typically used to prioritize protection areas or actions when combined with measures that relate to severity or impact of the contamination. A common approach is to designate groundwater supply protection areas as areas with high beneficial use where the contamination would cause the greatest impact(s) (Foster et al. 2002). These groundwater supply protection areas are known as wellhead protection areas (WHPAs) and sole source aquifers (SSAs) throughout the U.S., and Ground Water Management Areas (GWMAs) in Washington State.

The main types of protection areas that are relevant for the groundwaters of Snohomish County, as shown in Figure 1.0, include the following:

- **Wellhead protection areas (WHPAs):** The Wellhead Protection Program was initiated under section 1428 of the Safe Drinking Water Act. The EPA approved Washington's wellhead protection program in 1994. There are approximately 15,500 reported domestic water-wells in Snohomish County. These water wells are either private or public water systems. Private systems generally serve one connection and typically consist of a well serving a single home (Snohomish County PWSWM 2004). Washington State classifies public water systems by size into either Group A systems or Group B systems. Group A systems serve 15 or more connections. There are 290 Group A public water systems in the County. Pursuant to Chapter 246-290-135 WAC these systems are required to: (1) delineate the 1, 5, and 10-year Time of Travel wellhead protection areas for each source, (2) conduct an inventory for potential contaminant sources, and (3) collect and submit information to Washington State Department of Health (DOH) for a sensitivity or vulnerability assessment of the source water. In contrast, Group B systems are those public water systems that serve 2-14 connections and are arbitrarily assigned 600-foot fixed radius delineations as the wellhead protection area default values. There are approximately 375 Group B systems operating in the County (DOH 2004).

  The delineation of WHPAs can be done using a variety of methods, ranging from the simple fixed radius to the complex model-derived delineations. Several authors, U.S. EPA (1993); Swanson (1992); Cleary and Cleary (1991), have outlined the most commonly used methods and discussed the advantages, disadvantages and relative costs for each method. Table 1.1 summarizes these discussions. A general problem with all wellhead boundary determinations is that the boundaries are time and stress dependent (i.e., they change in response to changing recharge rates, changing patterns, and the influence of other pumping wells).

Table 1.1 Commonly Used Methods for Wellhead Protection Areas Delineation

(Sources: U.S. EPA 1987, updated 1993; Swanson 1992; Cleary and Cleary 1991)

Delineation Method	Description of Wellhead Boundary	Advantages	Disadvantages	Relative Cost/ Comments	Estimated Hours/ Location
Arbitrary Fixed Radii	Circular boundary at an arbitrarily selected distance criterion threshold value	Easy, inexpensive, quick and requires little technical expertise.	Heterogeneous and non-isotropic conditions make selection of radius difficult, May tend to over- or under-protect well recharge areas.	Low / Large number of wells can be completed in a short amount of time.	~ 1
Calculated Fixed Radii	Circular boundary designated whose radius is determined by a specific time of travel threshold	Easy, inexpensive, relatively quick, and provides increased accuracy over arbitrary fixed radii method	Heterogeneous and non-isotropic conditions cause inaccuracies in radius calculation	Low / More expensive than arbitrary fixed radius method because of data requirements	~3-5
Simplified Variable Shapes	Standardized shape designated based on hydrogeologic and pumping conditions found at wellhead	Implementation of shape designation is quick and inexpensive after standard shapes have been developed.	Initial development of standardized shapes is moderately expensive and requires significant data collection	Low / Initial development costs very high	~2-5 (initial development is >200 hours)
Analytical Methods	Boundary represents the zone of contribution as calculated using an analytical method, such as uniform flow equations	Very accurate if data are available and region lacks hydrogeologic complexities	Results not as accurate as numerical flow/transport models.	Medium / Depends on availability of data	~2-20
Hydrogeologic Mapping	Boundary based on flow boundaries mapped using geologic, geophysical and/or dye tracer data	Works well in settings with near-surface flow boundaries and highly anisotropic aquifers	Requires high level of expertise and significant data collection, Doesn't work well in large or deep aquifers.	Medium – High / Depends on availability of data	~4-20
Flow/Transport Models	Shape/size found using particle tracking within a groundwater flow model	High potential for accurate boundary, incorporates hydrologic boundaries	Requires high level of expertise and significant data collection	High Depends on complexity of region	~10-100

- **Sole source aquifer areas.** The Sole Source Aquifer Program was established under section 1424(e) of the Safe Drinking Water Act. It authorizes the EPA administrator to determine that if contaminated, an aquifer that is the "sole" or principal source of drinking water in an area would create a significant hazard to human health. An aquifer is determined to be a principal or "sole" source if it supplies at least 50% of the drinking water consumed in the area overlying the aquifer. Guidelines also stipulate that these aquifers can have no alternative drinking water source(s) that could physically, legally, and economically supply all those who depend upon the aquifer for drinking water.

  Sole source aquifer (SSA) designations can be proposed by an individual, corporation, company, association, partnership, state, municipality, or federal agency. The petitioner must provide the EPA with all hydrogeologic and drinking water usage data, and other technical and administrative information for designation. The designation decision process usually takes at least 6 months from the time the petitioner sends a complete petition. If approved, federally funded projects that have the potential to contaminate the aquifer must be reviewed by the EPA. However, proposed projects that are funded entirely by state, local, or private concerns are not subject to EPA review. Snohomish County currently has two designated sole source aquifers—the Cross Valley Aquifer, located in the Clearview-Maltby area; and the Newberg Area Aquifer, located east and south of the Pilchuck River. Both were designated in 1987 (US EPA 1995).

  The sole source aquifer program provides limited protection to groundwater resources and only protects drinking water supplies. It should not be viewed as a comprehensive groundwater protection program. Designating an aquifer as a sole source aquifer does not imply that it is more sensitive to contamination than any other aquifer. In addition, many sensitive aquifers remain undesignated simply because no one has filed a petition on their behalf, or because drinking water consumption patterns above the aquifer did not qualify it for SSA status. The sensitivity of an aquifer to contamination is best assessed with site-specific hydrogeological assessments in combination with other factors such as a project's design, construction practices, and long-term site management. For these reasons SSA status should not be used as the only determining factor for land use decisions that may impact groundwater quality.

- **Ground Water Management Areas (GWMAs)** Under the requirements of Chapter 173-100 WAC, Snohomish County established a groundwater management plan (GWMP) associated with GWMAs. In 2001, the Snohomish County GWMP was certified as being consistent with the intent of Chapter 179-100 WAC, to "protect ground water quality, to assure groundwater quantity, and to provide for efficient management of water resources for meeting future needs while recognizing existing water rights."

Combining sensitivity maps with measures that relate the value of the resource has been used in numerous cities and countries (Ducci 1999; Foster et al. 2002), and is the best available method for prioritizing critical aquifer recharge areas. This approach is firmly rooted in the literature and has become the framework for programs mandated and recommended by both the U.S. Environmental Protection Agency (EPA) and the World Bank (US EPA 1997; Foster et al. 2002).

There are limitations to using this prioritization methodology in water quality and quantity assessments (King County 2004). The most noteworthy are listed below.

- Aquifer sensitivity maps represent a major simplification of naturally complex geologic and hydrogeologic processes making them appropriate only for guiding groundwater protection policy.
- The sensitivity maps can overstate the risk in some cases. For instance, areas with a shallow water table may not have a high contamination potential if they fall within a discharge area.
- This methodology is only appropriate for measuring the sensitivity of contamination for the shallowest aquifer. It does not acknowledge the effect of confining units in the subsurface and their ability to protect deeper aquifers.
- This methodology assumes a universal contaminant, and in any given situation sensitivity may vary depending on the type, properties and attenuation potential of a particular pollutant (Foster et al. 1998).
- This methodology was specifically developed, and is best suited for water quality evaluations that project existing or potential contaminant loads on the highest risk areas to create contaminant hazard maps.

Methods for Determining Critical Aquifer Recharge Areas

A CARA delineation is based upon the sensitivity of aquifer(s) within a designated area. Guidance published by the Washington Department of Community, Trade and Economic Development (CTED) specifies that aquifer vulnerability is the foundation for a determination of a CARA (WA OCD 2002). In most cases however, sensitivity cannot always be calculated because sufficient information does not exist to determine an aquifer's physical properties (Focazio et al. 2002). Exceptions to this general rule that exist in the state of Washington include Clark, North Thurston, and Franklin Counties. These specific areas have been subject to intense hydrogeologic characterizations due to the occurrence of groundwater contamination, thereby making it possible to assess sensitivity. Washington State guidance (WA DoE 2000) suggests that a jurisdiction attempt to determine an aquifer's sensitivity in the absence of sufficient hydrogeologic data. The recommended approach is a conservative approach to sensitivity determinations and provides a worst case scenario for contaminant movement in the subsurface. Local governments are encouraged to consult with qualified scientific experts or teams of experts to help identify and determine if more current valid scientific information exists and assess its applicability to the relevant critical areas.

In 2001, Snohomish County followed these guidelines by assembling a team of qualified scientific experts to identify available scientific information, assess its applicability to the designation of Critical Aquifer Recharge Areas and draft development regulations to protect such areas. A Technical Advisory Committee was formed to provide the County with a broad range of scientific and technical expertise. The committee was comprised of representatives from the U.S. Environmental Protection Agency, U.S. Geological Survey, Tulalip Tribe, Washington State Department of Health, Snohomish Conservation District, Snohomish Health District, City of Everett, City of Marysville, various divisions of the Snohomish County Public Works Department, water purveyors, and private hydrogeology consultants.

The development of the draft Critical Aquifer Recharge Area map and associated regulations evolved from interaction between the Technical Advisory Committee, Adolfson Associates, Inc., and Golder Associates, Inc. Three formal Technical Advisory Committee meetings were held between May and September 2000. In preparation for these meetings, the committee reviewed and evaluated available supporting materials.

The Technical Advisory Committee and County consultants initially reviewed provisions of the state's Growth Management Act and the Minimum Guidelines to Classify Agriculture, Forest, Mineral Lands, and Critical Areas (Chapter 365-190 WAC) relevant to the designation of Critical Aquifer Recharge Areas. The Technical Advisory Committee also reviewed the Guidance Document for the Establishment of Critical Aquifer Recharge Area Ordinances (Ecology 2000).

The Technical Advisory Committee then assessed the principal sources of information regarding the hydrogeology of Snohomish County: *The Ground-Water System and Ground-Water Quality in Western Snohomish County, Washington* (Thomas et al 1997) and the *Snohomish County Ground Water Management Plan* (Snohomish County 1999). From these documents, as well as supplemental information provided by the Technical Advisory Committee, a draft Critical Aquifer Recharge Area map was developed. Snohomish County's current sensitivity map, developed by the USGS (Thomas et al. 1997), uses two of these parameters, net recharge (R) and depth to the water table (D).

The draft GWMA/CARA map currently incorporates the following four types of Critical Aquifer Recharge Areas defined for Snohomish County: low, moderate, and high sensitivity areas as identified by Thomas et al. 1997; Sole Source Aquifers; public water system Wellhead Protection Areas (as described above); and an "Undefined," category that allows the County to address areas of uncertainty where insufficient data are available to support classification (or incorporation of future best available science).

The process of formulation of the current groundwater protection ordinance followed a parallel pathway. The Technical Advisory Committee evaluated a number of adopted Critical Areas development regulations from other Puget Sound counties to gain more specific information regarding accepted management practices for protection of aquifer resources. Those regulations included the following: Skagit County Critical Areas Ordinance (Chapter 14.06 Skagit County Code), Kitsap County Critical Areas Ordinance (Chapter 18.16 Kitsap County Code), Whatcom County Critical Area Ordinance (Chapter 16.16 Whatcom County Code), Pierce County Critical Areas Ordinance (Chapter 18 E Pierce County Code), Thurston County Critical Areas Ordinance (Chapter 17.15 Thurston County Code), and Mason County Resource Ordinance (Chapter 170.1 Mason County Code). The Technical Advisory Committee and County consultants recommended that mitigation measures and management practices be based largely on those recommended in the Snohomish County Ground Water Management Plan and those applied by other jurisdictions within the Puget Sound region.

Based on the recommendations of the Technical Advisory Committee, the County consultants developed a preliminary draft of the development regulations, which were distributed to the committee for review and comment. The comment period extended from early January 2001 to mid-April 2001. The County and its consultants evaluated the comments received from the committee, prepared a responsiveness summary regarding the comments, and incorporated appropriate modifications to the draft development regulations.

In 2002, the County continued to review its groundwater regulations and consolidated a variety of previously separate land use codes "to provide a unified set of standards and procedures to regulate building and land development within unincorporated Snohomish County," this Unified Development Code (UDC) became effective February 1, 2003, and replaced the previous interim groundwater protection ordinance.

The County has continued to fine tune its groundwater protection policies and ordinances in the current Critical Areas Regulations (CAR) update. The recent effort to update and review the draft CARA regulations and associated map ensures the use of best available science in updating the County's CARA regulations.

Special Areas or Issues of Concern

Many land-use activities can potentially affect the quality or quantity of groundwater recharge. If these activities occur above aquifer recharge areas critical to groundwater quality and quantity, it is prudent to implement groundwater protection measures to protect the groundwater resources of the County. Under the Growth Management Act (RCW 36.70A(1)), protection of the quality and quantity of groundwater used for public water supplies must be addressed within a County's comprehensive plan. Snohomish County is currently in the process of updating its comprehensive plan and has incorporated special areas and issues of concern with regard to groundwater in its long-term planning. The discussion below incorporates the work presented in the recent Draft Environmental Impact Statement under the state's SEPA process for that update (Snohomish County DEIS 2004).

Groundwater Quantity

The amount of groundwater available for use in an aquifer is largely controlled by the amount of recharge to and discharge from the aquifer. Recharge to a groundwater system occurs primarily by infiltration (the process by which water enters the soil) and percolation (the downward movement of water through the soil) of precipitation from the surface. Other sources of recharge can include seepage from rivers, streams, or lakes; vertical and lateral groundwater flow between aquifers; and seepage from excess irrigation water and septic-system effluent. Discharge from a groundwater system occurs naturally to surface water bodies such as streams, lakes, wetlands, and springs; as the result of pumping from wells; as vertical and lateral groundwater flows between aquifers; and as evaporation from the ground and transpiration from vegetation (together referred to as evapotranspiration) (Dunne and Leopold 1978).

The amount of recharge to the groundwater system varies throughout the County depending on factors including precipitation, surficial geology, soil properties, vegetation, and land use. Generally, groundwater recharge is greater within the eastern portions of the GWMA, and associated CARAs, because of generally higher annual precipitation and fewer densely urbanized areas, which are more common in the southwest portion of the County (Thomas et al. 1997).

Impacts to groundwater quantity generally result from:

- Changes in population that increase demand for groundwater as a potable water supply. Many areas of Snohomish County rely heavily on groundwater. As these communities grow, there is an increased demand for potable water to supply homes, businesses, and industries. Depending on specific circumstances, increased groundwater demand can lower water tables, reduce baseflow discharge to streams, and require new wells to be constructed, especially if instead of returning to the source, the water is diverted from a basin. Current water rights may not be adequate to support increased population in some areas (Hirschey 2004).
- Changes in land use that reduce groundwater recharge. Urban development causes land to be paved, creating impervious surfaces. Impervious surfaces do not allow precipitation to recharge aquifers, which can lower water tables and reduce baseflow to streams, lakes, and wetlands. Often the effect of reduced recharge is seasonal, and is not seen until the dry season when water tables are naturally lower. Reductions in recharge during the wet season can carry over into the dry season (Snohomish County DEIS 2004).

Groundwater Quality

Groundwater quality in the GWMA, and associated CARAs, was documented by a USGS study in 1997, and it was found that the groundwater quality in western Snohomish County is generally good, with no appreciable widespread contamination. The study sampled for chemical constituents that are associated with agriculture, industry, commercial activities, septic systems, and seawater intrusion. Elevated concentrations of nitrate and ammonia were found in isolated areas due to agricultural activities and septic systems but no regional patterns of contamination were identified. The USGS study concluded that septic systems have not caused any appreciable widespread groundwater contamination and that there was no correlation between the septage-related compounds and nitrate and ammonia concentrations that were observed. In the time since the 1997 USGS study, the County's water quality staff have identified potential septic problems in certain areas of the County where bacterial levels have exceeded state standards in many of the streams they routinely sample (Thornburgh 2003). While Snohomish County has not completed any source identification, other regional studies have identified human waste as a source warranting further investigation of septic systems (City of Seattle 1993; University of Washington 2000).

Elevated iron and manganese concentrations were found to be fairly common in Snohomish County, and the USGS (1997) study reported that 20% of the samples of iron and 41% of the samples of manganese exceeded secondary water quality standards. These secondary standards are set primarily for aesthetic and taste reasons, and do not represent health hazards.

Another natural water quality problem found in western Snohomish County was the presence of arsenic. Its occurrence was detected in the Getchell Plateau during two groundwater sampling events conducted by Snohomish County's Groundwater Program under a grant from Washington State Department of Ecology in 2001. In the 1997 USGS study (Thomas et al. 1997) arsenic was detected in 63% of the 297 sampled wells and 18% of those sampled had concentrations greater than 10 micrograms per liter. This exceeds the current proposed maximum contaminant level (10 micrograms per liter) for drinking water, which will take effect in 2005. Of the 64 private drinking water wells sampled in the fall of 2002 and spring of 2003 in the Getchell Plateau, arsenic levels higher than 10 micrograms per liter were detected in ten wells. Therefore, ten households receive water from their well that exceeds the current maximum contaminant level (MCL) for arsenic. There are no regulatory mechanisms, at the Federal, State, or County levels in place to compel or encourage these individuals to address the potential health risks associated with the arsenic in drinking water.

Seawater intrusion was found only in isolated areas; no appreciable seawater intrusion was observed in western Snohomish County in the 1997 USGS study.

Snohomish County impacts of concern to groundwater quality result primarily from:

- Land uses that produce higher levels of non-point source pollution, such as urban run-off or septic disposal. These land uses distribute contaminants over large areas, which accumulate over long periods of time in groundwater or other water bodies. It is usually difficult to attribute this type of contamination to a single source (Snohomish County DEIS 2004).

- Land-uses associated with point source pollutants, such as industrial facilities. These land uses can produce contamination that enters the groundwater at a specific point (Snohomish County DEIS 2004).

Table 1.2 shows the various types of contaminant sources that can be associated with different land uses.

Based upon literature review, historical data on activity related releases of contaminants, existing planning documents (e.g., the Snohomish County Groundwater Management Plan, 1999, and Snohomish County DEIS for GMA Comprehensive Plan 10-Year Update, 2004), federal, state, and local regulatory control, and model CARA provisions from Washington State agencies (WA OCD 2002; WA State Dept. of Ecology 2000), the following activities were selected, as outlined in the Council's newly drafted ordinance, for additional protection measures within Snohomish County:

Industrial/Commercial Land Uses

- Underground Storage Tanks
- Above Ground Storage Tanks
- Surface Mining (Metals and Sand and Gravel)
- Animal Feedlots
- Automobile Washers
- Hazardous Waste Generator
- Chemical Treatment Storage and Disposal Facilities
- Wood Preserving/Treatment
- Junk Yards and Salvage Yards
- Oil and Gas Drilling
- Pesticide Storage and Use
- Sawmills
- Solid Waste Handling and Recycling Facilities

Municipal/Residential Land Uses

- Landfills (Hazardous or dangerous waste, municipal solid waste, special waste)
- On-site Sewage (Septic) Systems

Miscellaneous Land Uses

- Injection wells
- Waste Water Application to Land Surface

There are many land-use activities that can potentially affect the quality or quantity of groundwater recharge. Any potential land-use activity that stores, uses, or produces known contaminants of concern (constituents found to be a risk to human health and capable of groundwater transport) and has a sufficient likelihood of releasing such contaminants to the environment at detrimental levels is considered a threat. Any land-use that can reduce the quantity of recharge to the aquifer to a significant degree is also considered to be a threat. If these activities occur above aquifer recharge areas critical to groundwater quality and quantity, it is prudent to implement groundwater protection measures in those areas to protect the groundwater resources of the County.

Each of the contaminant sources/activities being considered for further regulation within Snohomish County has been identified as a groundwater impacting activity and is listed with its associated statute, regulation, or guidance in Table 1.3. The use may be permitted only in such conditions where the County determines, with required mitigation and controls, (conditioned as necessary to protect critical aquifer recharge areas in accordance with the applicable state and federal regulations), that the use has no reasonable probability of impacting present or future aquifer use for potable water.

Table 1.2. Potential Groundwater Contaminant Sources by Land Use

Land Use	Description	Specific contaminants
Agriculture	Active farming operations, irrigation	Pesticides, fertilizers
	Animal feedlots, manure storage	Livestock sewage wastes, nitrates, phosphates, chloride, chemical sprays and dips for controlling insect, bacterial, viral, and fungal pests, coliform bacteria, viruses
Commercial	Airport	Jet fuels, de-icers, batteries, diesel fuel, chlorinated solvents, automobile wastes, heating oil, building wastes
	Auto shop	Paints, solvents, metals
	Car washes in unsewered areas	Soaps, detergents, waxes, miscellaneous chemicals, metals, motor vehicle fluids
	Dry cleaning	Solvents (tetrachloroethylene, petroleum solvents, freon), spotting chemicals (trichloroethene, ammonia, rust removers).
	Gas service station	Gasoline, oils, solvents, miscellaneous wastes
	Railyards, railroads	Spills
	Scrap/junkyard	Oil, gasoline, antifreeze, PCB contaminated soils, lead acids, batteries
	Laundromats in unsewered areas	Detergents, bleaches, fabric dyes
Industrial	Gravel and sand pits	Spills, miscellaneous chemicals, bacteria
	Mining	Cyanide, sulfides, metals, acids drainage
	Paper mill	Metals, acids, minerals, sulfides, chemicals, sludges, chlorine, hypochlorite
Residential	Fuel storage tanks	Gasoline, diesel fuel, other petroleum products
	Water well	Potential conduit for pollutants to enter groundwater
	Septic tanks	Septage, coliform bacteria, viruses, nitrates, heavy metals, synthetic detergents, cooking and motor oil, bleach, pesticides, paints, paint thinner, septic tank cleaner chemicals, chlorides, sulfate, calcium, magnesium, potassium, phosphate

Source: Wisconsin Dept. of Natural Resources 2003.

Table 1.3. Statutes, Regulations, and Guidance Pertaining to Groundwater Impacting Activities

Activity	**Statute – Regulation – Guidance**
Above Ground Storage Tanks	Chapter 173-303-640 WAC
Animal Feedlots	Chapter 173-216 WAC, Chapter 173-220 WAC
Automobile Washers	Chapter 173-216 WAC, Best Management Practices for Vehicle and Equipment Discharges (Washington Department of Ecology WQ-R-95-56)
Below Ground Storage Tanks	Chapter 173-360 WAC
Chemical Treatment Storage and Disposal Facilities	Chapter 173-303-182 WAC
Hazardous Waste Generator (*Boat Repair Shops, Biological Research Facility, Dry Cleaners, Furniture Stripping, Motor Vehicle Service Garages, Photographic Processing, Printing and Publishing Shops, etc.)*	Chapter 173-303 WAC
Injection Wells	Federal 40 CFR Parts 144 and 146, Chapter 173-218 WAC
Junk Yards and Salvage Yards	Chapter 173-304 WAC, Best Management Practices to Prevent Stormwater Pollution at Vehicles Recycler Facilities (Washington Department of Ecology 94-146)
Oil and Gas Drilling	Chapter 332-12-450 WAC, Chapter 173-218 WAC
On-Site Sewage Systems (Large Scale)	Chapter 173-240 WAC
On-Site Sewage Systems (< 14,500 gal/day)	Chapter 246-272 WAC, Local Health Ordinances
Pesticide Storage and Use	Chapter 15.54 RCW, Chapter 17.21 RCW
Sawmills	Chapter 173-303 WAC, Chapter 173-304 WAC, Best Management Practices to Prevent Stormwater Pollution at Log Yards (Washington Department of Ecology, 95-53)
Solid Waste Handling and Recycling Facilities	Chapter 173-304 WAC
Surface Mining	Chapter 332-18-015 WAC
Waste Water Application to Land Surface	Chapter 173-216 WAC, Chapter 173-200 WAC, Washington Department of Ecology Land Application Guidelines, Best Management Practices for Irrigated Agriculture

Summary

Mapping Critical Aquifer Recharge Areas provides the general framework within which to base groundwater quality and quantity protection policy. The County has designated four classes of Critical Aquifer Recharge Areas or potential Critical Aquifer Recharge Areas through the

GWMA/CARA Map. Snohomish County, using a modified version of the “DRASTIC” model, identified areas of low, moderate, and high sensitivity and then overlaid water supply protection areas (commonly called wellhead protection areas, sole source aquifers, and GWMAs) to identify the County’s critical aquifer recharge areas. The following four areas are designated as current or potential Critical Aquifer Recharge Areas:

(1) Sole Source Aquifers designated by the U.S. Environmental Protection Agency in accordance with the Safe Drinking Water Act of 1974 (Public Law 93-523).

(2) Areas encompassed by the ten-year time of travel zones of Group A public water system Wellhead Protection Areas determined in accordance with delineation methodologies specified by the Washington Department of Health under authority of chapter 246-290 WAC.

(3) The Snohomish County Ground Water Management Area designated by the Washington Department of Ecology under authority of chapter 246-290 WAC. The Ground Water Management Area can be further classified as High, Moderate, and Low Susceptibility Critical Aquifer Recharge Areas based on degree of sensitivity to contamination.

(4) Undefined areas are those where insufficient data are available to support classification or areas that will be defined based on future best available science.

The boundaries of the designated areas are delineated in the GWMA/CARA Map, Revised: July 30, 2003.

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Chapter 2 – Frequently Flooded Areas

Introduction

Snohomish County defines "frequently flooded areas" as "flood hazard areas" and regulates them to protect members of the public from injury, loss of life, property damage or financial loss due to flooding. In the context of protecting public safety by addressing natural hazards, the best available science should be used to provide policymakers:

- a delineation of the extent of the hazard;
- an assessment of the probability of the hazard occurring; and
- an estimate of the potential damages resulting from the hazard.

This chapter divides flood hazards into four categories: Riverine Inundation; Coastal Flooding; Tsunami; and Other Flood Hazards. It describes the probabilities, delineation methods and potential damages associated with each hazard type, with a focus on riverine flood hazards.

Natural Floodplain Functions

Floodplains are low-lying areas adjacent to rivers that are formed chiefly of river sediment and are subject to flooding. Floodwaters rise above the natural containment levels in rivers and streams as a result of periods of intense rainfall and/or snowmelt. Flooding is a natural process that results in inundation and bank erosion. Bank erosion is the process whereby river and stream banks are scoured or undermined by high velocity erosive flow. Flooding exacerbates the risk of damage to people and properties, but it is also important for creating and maintaining healthy aquatic and riparian habitats.

The recognized benefits of a naturally functioning floodplain include the storage and conveyance of flood waters, the recharging of groundwater, the maintenance of surface water quality, and the provision of habitats for fish and wildlife.

Snohomish County Rivers and Streams

Major rivers in Snohomish County are the Skykomish River, including the North and South Forks, the Snohomish River, the Snoqualmie River, the Stillaguamish River, including the North and South Forks, and the Sauk River. These rivers descend from the crest of the Cascade Mountains to Puget Sound and are heavily influenced by snow and rain patterns in the mountains. Important tributaries and historic flood hazards include the Wallace River and Sultan River on the Skykomish, the Pilchuck River on the Snohomish, and Canyon Creek on the South Fork Stillaguamish. The Sultan River is the only regulated river in Snohomish County, with Culmback dam impounding Spada Lake, a reservoir with significant flood storage capacity. Numerous mid-sized stream systems drain the Cascade foothills and rural areas throughout the eastern County. Their flooding is generally governed by rainfall rather than snow melt runoff. In the western portions of the County, there are numerous small streams with moderate to high amounts of watershed development where flooding can be heavily influenced by stormwater runoff from urbanization.

Flood Hazards, Damages, and Methods of Delineation

When development occurs on or near floodplains, people and property become exposed to increased flood hazards. The following section describes the various types of flood hazards that occur in Snohomish County, the types of damages caused by exposure to the hazard, and the best available scientific methods used to delineate each type of hazard.

Inundation

National Flood Insurance Program (NFIP) Standard Methods

Inundation is the flooding of normally dry areas. There may be little to no velocity associated with the inundation. Mapping the inundation limits of the "100-year flood" forms the core of the National Flood Insurance Program (NFIP) flood hazard mapping mission, and hence serves as a national minimum standard that must be met. The "100-year flood" is a flood that has a 1% chance of occurring in any given year. Note that the standard chosen was a policy decision based on risk assessment, insurance rating and floodplain management needs, "while not imposing overly stringent requirements or the burden of excessive costs on property owners" (FEMA 2002). Over the course of a 30- year mortgage, a floodplain property has a 1 in 4 chance of experiencing the 100-year flood.

FEMA has standardized methods approved for use nationwide in order to map the limits of the floodplain and predicted water levels (FEMA 2003). The methods detailed below represent standard practices, and are applicable to the determination of inundation limits and depths for all magnitudes of floods. Work is generally performed under the direction of professional engineers.

Delineation begins with a detailed hydrologic analysis. The purpose is to develop estimates of the probability of various magnitude floods. Long term stream gauge records; regional regression equations (Sumioka et al. 1998); or rainfall-runoff models are used to estimate the magnitude of peak flow that will occur for a given probability. Peak flow magnitudes are determined for the 1% annual chance flood, as well as the 10% (10-year), 2% (50-year) and 0.2% (500-year) annual chance events. In some cases, the volumes and duration of the various floods may also be estimated.

Detailed hydraulic analysis is then performed. A computational hydraulic model is constructed that contains a representation of the important floodplain, channel, land cover and structural features (such as bridges and levees) that govern flood levels. When available, the model is calibrated to match observed data taken from historic flood events. The flood flows determined by the hydrologic analysis are input into the model, which calculates the flood depths and velocities. The hydraulic model output is then overlaid on the floodplain topography and the flood depths, elevations, and inundation limits are delineated (FEMA 2003).

As roads, bridges, and most utilities are resistant to water damage, significant inundation damages are generally limited to buildings. Inundation of buildings often requires extensive replacement of sheetrock, carpeting, flooring and utilities. Repeated inundation can lead to rot of wood structural members. Damages to homes can be estimated using structure and content values and information from the hydrologic and hydraulic studies. FEMA has developed software to estimate these damages based on costs from flood insurance claims nationwide

(FEMA 2003b). A similar package is available from the Corps of Engineers (USACE 1998). These methods integrate the probability of flooding with the expected damages to calculate amortized expected annual damages.

NFIP Method Shortcomings

Larson and Plasencia (2001) reviewed trends in riverine flood damages and concluded that "annual flood losses in the United States continue to worsen in spite of 75 years of federal flood control and 30 years of the National Flood Insurance Program". The 1990s was the costliest decade of the century in terms of flood damages (Larson and Plasencia 2001). The damages resulting from flooding continue to rise despite the fact that between 1978 and 2002 the percentage of "Pre-FIRM" buildings (structures that predate the entry of a community into the NFIP and hence are much more likely to be built at low flood-prone levels) in the NFIP dropped from 70% to 26%, and between 1977 and 2002 the total number of NFIP policies increased from 1.2 million to 4.3 million (FEMA 2002).

Shortcomings with the basic NFIP flood hazard protection approach include both policy and science issues. Issues associated with scientific methods include the following.

Outdated floodplain mapping

Rivers are dynamic, changing systems. After the initial mapping was finished, the NFIP program had very few funds to update the maps. The mapping for most large rivers in Snohomish County was completed in the early 1980s, so they are now 20-25 years old. Changing climate, land use and channels often results in increased flows and flood levels. In the late 1990s, FEMA identified the need for more updated mapping and implemented the Map Modernization program in response. They estimate approximately $26 billion in damages can be avoided by updating the maps nationwide (FEMA 2001). Error in flood levels up to 4 feet due to outdated mapping in Snohomish County have been found (Snohomish County 2004b).

Floodplain Storage

Floodplains act to temporarily store floodwaters and then release them after the peak of the flood has passed. This storage results in decreases in flow rates down-valley.

Many of the models used for floodplain mapping to date have been steady-state models. These models calculate flood levels based on a constant flood flowing through the river, and do not account for attenuation of flows associated with floodplain storage. When the standard NFIP floodway/flood fringe is evaluated, the loss of this floodplain storage due to flood fringe development is not accounted for, leading to underestimation of the flows that will occur downstream (Larson and Plasencia 2001). In one case study, when the effects of lost floodplain storage were accounted for in a standard NFIP "1 ft rise floodplain," the actual predicted increases in flood elevations were 2.3 ft, along with a 19% increase in peak flow (Mecklenburg County 1999).

Floodplain storage effects can be accounted for by using unsteady-state (dynamic) models. These models calculate flows and flood levels at time steps throughout a simulation. A flood wave hydrograph is input to the model, and the storage and attenuation functions of the floodplain are accounted for correctly.

Future Conditions

Until 2001, FEMA would only allow current conditions data to be placed on the flood insurance rate maps (FEMA 2002). In part this was due to the fact the maps are used for actuarially rating flood risk, which must be calculated based on current risk, not future risk (Larsen and Plasencia 2001).

In fact, future flood risk is known to be generally increasing due to both development and climate change. The impacts of development on peak flows are well known. In the smaller watersheds of western Snohomish County where the majority of development is taking place, extensive work to predict future flows resulting from full development in the watersheds has been done. Consideration of predicted future flows have been considered in identifying capital improvement programs (Snohomish County 2002).

The Pacific Northwest has seen increasingly warmer and wetter conditions in the last century (Mote 2001). Climate change predictions for western North America (IPCC 2001) and the Pacific Northwest region (Mote 2001) indicate continued warming at rates greater than the global average. Moderate increases in precipitation are also predicted (Mote 2001). Global warming is also expected to lead to more severe weather extremes, including larger precipitation events (IPCC 2001).

These factors indicate that flooding is likely to increase in severity on the rivers of Snohomish County in the coming decades. The consequence is that structures, most of which will last 50 or more years, will be subject to greater damages over their life than what would be predicted by the current risk. By evaluating likely future conditions in inundation mapping efforts, the true risk and consequent expected damages over the life of the structure can be more accurately determined.

Coastal Flooding

Coastal flooding in Snohomish County is generally caused by intense winter storm systems arriving from the Pacific Ocean. Low pressure associated with these systems causes an increase in local sea levels. Strong winds over distances of open water (fetch) stack up the water on the downwind shore. When these storms occur during periods of high tides, extreme water levels result, along with larger waves. Coastal landforms can magnify the effects of wind driven waves, creating local areas with larger hazards.

Coastal flooding creates inundation hazards through high water levels. Large waves can contain debris and generate significant forces as they break against the shoreline and associated development.

Similar to riverine inundation mapping, FEMA has specifications that form the national standard for determination of coastal flood hazards (Appendix D in FEMA 2003). Statistical analysis of long-term tide gauge records or storm surge models are used to determine the “1% annual chance still water elevations” (the elevation that would be reached by a storm induced high tide without consideration of wave size). Depending on the coastal topography and geology, additional analyses for wave size, wave run-up, and coastal erosion are conducted. The analyses are combined into a single flood hazard delineation map.

Global sea levels rose steadily over the course of the 20th century at rates of 1-2 mm/year, for a total central estimate of 15 cm (0.5ft) (IPCC 2001). The central value predicted by multiple climate change models is a further increase in global mean sea level of 48 cm (1.6ft) from 1990 to 2100. Increases in storm severity may also increase wave heights and storm surge elevations (IPCC 2001). As with riverine inundation issues, the tools and methods in use are adequate, but future conditions must be considered to accurately quantify the increasing risk levels over time.

Tsunamis

A tsunami is a wave train, or series of waves, generated in a body of water by an impulsive disturbance that vertically displaces the water column. Earthquakes, landslides, volcanic eruptions, explosions, and even the impact of cosmic bodies, such as meteorites, can generate tsunamis. In Puget Sound, the following potential tsunami sources have been identified: earthquakes generated by local faults, delta slope failures, submarine landslides and terrestrial landslides have been identified as the potential tsunami sources (Gonzalez et al. 2002).

Earthquakes can directly cause tsunamis by the rapid uplift or subsidence of the seabed along fault zones. An earthquake of magnitude 7 or more is known to have occurred around A.D. 900-930 on the Seattle Fault Zone (Atwater 1999 in Gonzalez et al. 2002). Tsunami deposits attributed to this earthquake have been mapped in the Snohomish River delta, along with additional tsunami deposits dated to around A.D. 130-530 and A.D. 420-640 (Bourgeois and Johnson 2001).

Submarine (underwater) landslides can originate from the delta slopes of large rivers. The Puyallup, Duwamish, and Snohomish River deltas have been identified as priority areas for study of delta failure (Gonzalez et al. 2002). Submarine landslides on the Puyallup delta in 1894 and 1943 caused infrastructure damage in Tacoma; the Snohomish River delta is identified as similar in structure to the Puyallup (Gonzalez et al. 2002). Submarine landslides can also originate from steep underwater slopes not associated with river deltas. In Western Washington, such slides have been mapped near fault zones in Puget Sound, Lake Washington and Lake Sammamish. An earthquake is considered the most likely trigger of worst case submarine landslides in the region, but the Puyallup River delta record shows that these slides can occur without seismic events (Gonzalez et al. 2002).

Terrestrial landslides can create a tsunami by the displacement of water upon entry of the sliding mass. Three days after the Magnitude 7.1 Olympia earthquake of 1949 a landslide occurred at the Tacoma Narrows that generated a tsunami (Chleborad 1994 in Gonzalez et al. 2002). Shipman (2001) documents the historic accounts of the Snohomish people of a large landslide from Camano Head in the 1820s that initiated a tsunami. The tsunami propagated southward and washed over the low lying areas of Hat Island, drowning some tribal members. There is no indication the slide was seismically induced. Low lying coastal areas and river deltas are at risk from tsunamis. In Snohomish County, these areas include the coastline and the Snohomish and Stillaguamish river deltas. As tsunamis approach shallow water, they slow and gain in height.

Tsunami height, inundation and velocity mapping is performed using numerical models similar in concept to those used in riverine flood mapping. The models require an estimate of the displacement of water due to an earthquake or other source, and a high resolution digital elevation model of the seafloor and coastal areas. Given an initial displacement, the models calculate the propagation of the wave from the source, calculating elevations and velocities at each time step.

Detailed tsunami modeling of the Elliot Bay area in Seattle has been completed by the NOAA Center for Tsunami Mapping Efforts (TIME). The earthquake scenario chosen was a magnitude 7.3 quake that simulates the A.D. 900-930 quake. This was the quake inferred to have caused the tsunami deposits in the Snohomish River delta (Bourgeois and Johnson 2001). Vertical seabed displacement of up to 7 meters causes a tsunami of around 6m (measured above mean high water) to propagate into Elliot Bay. This results in wave run-up of up to 10m against steep bluffs, and inundation of flat low lying areas up to 1 mile inland. Large areas have predicted depths exceeding 2m and velocities exceeding 2m/s (Titov et al. 2003).

In similar mapping TIME performed for Bellingham, based on a Cascadia subduction zone fault, inundation extended about 4 miles up the Nooksack River delta, depths exceeded 2m and velocities 5m/s up to two miles inland (Walsh et al. 2004).

Tsunami velocities are significantly faster than those caused by riverine flooding in delta areas. Tsunami damages are caused by inundation, and by the entrainment of any materials able to be transported by the wave – a tsunami can have enough force to move large logs, vehicles and other large heavy objects at significant velocities. Tsunamis can also cause rapid drawdown of coastal waters before or after the wave, pulling floating debris out to open water rapidly.

The greatest uncertainties in tsunami modeling occur in estimating the displacement mechanisms that cause the wave. In addition, the probability of occurrence of landslides and earthquakes large enough to initiate tsunamis is low and poorly known. Therefore, while the consequences of a tsunami can be catastrophic, the level of risk is uncertain. Further research is needed in estimating probabilities of large earthquakes, submarine and terrestrial slides. Detailed tsunami hazard and damage modeling should be considered for the Snohomish County marine shoreline and river deltas.

Other Flood Hazards

High Velocities/Debris

The mountainous terrain that defines the eastern portion of Snohomish County results in numerous rivers with steep gradients and consequently high water velocities during floods. High velocities can impart lateral loads to structures that exceed their capacity.

The heavily forested lands of these river headwaters and upper floodplains result in significant debris loading as channel migration, debris flows and landslides feed trees into the channel. A large tree being transported by a river during a flood may have enough momentum to severely damage the structures it impacts. Undersized bridges and culverts may be blocked by debris, increasing inundation hazards upstream, and the risk of failure of the structure through scour or roadway overtopping.

Earthquake Caused Subsidence/Liquefaction

Flood control structures in the lower Stillaguamish and Snohomish River Valleys are built of and placed upon seismically vulnerable soils (Snohomish County 2004). Multiple earthquake induced soil liquefaction and rapid subsidence events of up to 2 ft have been documented in the Snohomish River delta (Bourgeois and Johnson 2001). Thus, an earthquake can be expected to induce widespread levee failures and collapses. The diking and draining of the lower delta areas for agriculture have resulted in large areas subsiding to elevations well below high tide levels. The lands protected by the levees will then be flooded, even under low flow and normal tide conditions. The level of damages from this secondary flood hazard will likely be relatively low, as the areas are within the regulated floodplain and so most buildings are already elevated above the 100-year flood level. However, the triggering earthquake itself can be expected to cause widespread damage to buildings, infrastructure and utilities in these areas. Response and recovery efforts may therefore be complicated by the flooding.

Levee Breaches

Extensive levee systems exist in the Snohomish and lower mainstem Stillaguamish River valleys. These levees serve to exclude floodwaters from large tracts of land, and were generally constructed to facilitate the draining and conversion to agriculture of the fertile floodplains. The catastrophic failure of levees during floods can lead to localized erosion, velocity and inundation hazards that far exceed the magnitude of equivalent processes a river could generate under natural conditions. Levees can fail through overtopping, interior erosion through the levee or underlying soils, or soil failure within the levee or underlying soils (USACE 2000). The latter two failure mechanisms do not require that river levels exceed the top of the levee to induce failure. Rapid failure leads to hydraulic conditions similar to those encountered by dam breaches. Washington State regulates dams for public safety purposes that impound more than 10 acre-feet of water at the dam crest (WAC 173-175). Riverine levee systems hold back volumes far exceeding this threshold.

In Snohomish County, levee breach lengths have exceeded 1000 ft and scoured to depths over 50 ft. Severe land erosion can occur hundreds of feet behind the breached levee. Dimensions are similar to those found after the 1993 floods on the far larger Missouri River (SAST 1994). Levee breach widths and rates of development and flows can be estimated using methods developed for estimating breaching of earthen dams (Walther 2000). Some standard hydraulic models used for inundation mapping also incorporate dam and levee breach methods into them and can be used to estimate near-breach velocities – HEC-RAS river analysis system is one example (USACE 2002). CADAM (2000) provides a summary of research to date and technical issues with breach modeling.

The probability of levee breaches occurring during major floods is high in Snohomish County. Breaches have occurred in every large flood in recent decades. The specific location of breaches is much more difficult to predict. Virtually all Snohomish County levees are set at low levels of protection. Those on the Snohomish River are built to contain a 5-yr flood (Snohomish County 1991) and undergo extensive overtopping during larger floods. Hence, all potential failure mechanisms are potentially active. The scour depths and velocities that occur in the vicinity of breaches are sufficient to destroy any structures built there. Measurements of levee breaches from the local historic record and breach modeling techniques can be used to estimate distance behind levees where damaging erosion and velocities can be expected to occur.

Summary

The technical tools and methods used in the delineation of flood inundation areas are well established. The NFIP program provides national standards for the minimum level of analysis allowed. Regular updating of flood maps, correctly accounting for the loss of floodwater storage functions on downstream flows, and incorporating expected future conditions into the assessments are recommended in order to better quantify risks associated with inundation.

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Chapter 3 – Fish and Wildlife Habitat Conservation Areas

Introduction

Fish and wildlife habitat conservation means managing land to maintain species in suitable habitats within their natural geographic distribution so that isolated subpopulations are not created; it does not mean maintaining all individuals at all times (WAC 365-190-080(5)). Much of wildlife habitat occurs in or near aquatic areas. Consequently, this chapter will provide a thorough review of the functions and values provided by aquatic habitat. It will also encompass wildlife habitat that occurs outside of aquatic areas, the relationship of stormwater and habitat, and individual threatened or endangered wildlife species.

Aquatic Areas

The most basic functions of an aquatic area are the storage, purification, and transport of water. Aquatic areas also function as habitat for a large number of plants and animals. Specific types of aquatic habitats in Snohomish County include rivers, streams, lakes, ponds, wetlands, estuaries, marine nearshore areas, marine offshore/deepwater areas and shallow aquifers. These habitats and the species that use them are integrated parts of an aquatic ecosystem that has developed, and continues to develop, due to a myriad of climatic, geologic, and plant and animal interactions. Human uses and development of land and water often affects this ecosystem in profound ways, ultimately affecting the type and abundance of species that exist.

This review focuses primarily on the formation and habitat functions of aquatic and riparian areas and factors that influence those functions. Much of this discussion focuses on salmonids and their habitats in part because of their ecosystem, social, and commercial importance and due to their depressed population status. The Growth Management Act also requires that in enacting critical areas policies and regulations, that local governments give special consideration to anadromous fisheries. Also, because locally more is known about them than any other group of animals and their near-ubiquitous distribution and sensitivity to environmental change, salmonids are good indicators of habitat impacts and of the effectiveness of protection measures for aquatic systems and other aquatic species.

Despite this chapter's focus on habitats and species, it is important to note that aquatic areas and their ecosystems include people and provide many other socially and environmentally valuable benefits (often referred to as ecosystem services) including flood hazard reduction, conveyance of stormwater runoff, water supply, water quality purification, recreation, and navigation.

Processes that Form and Sustain Aquatic Areas and Species

Understanding how aquatic habitats and species are formed and sustained is essential in devising a strategy for their effective management. The following describes the physical and biological processes that are critical in this understanding.

The Role of Water

Water-generated energy (stored or kinetic) and the chemical properties of water set the stage for the formation and function of aquatic areas. Movements of water whether as slow-moving glaciers, flowing streams, tides or waves generate the energy necessary to scour, transport and deposit sediments (Richards 1982; Downing 1983). The scour, transport and deposit of sediments is dramatically illustrated in Figure 1.0 showing the Skykomish River near Sultan in 1938 (upper panel) and in 2001 (lower panel), the river having re-made itself over this time period. Storage of water, whether in surface features (ponds and wetlands) or in soils and sediments (shallow groundwater aquifers or hyporheic areas) provides for the near-surface availability of water (e.g., hyporheic flow and groundwater discharge) required by some species in aquatic and riparian areas often through periods of the year when little is available otherwise. In addition, the chemical properties of water allow for the dissolution, suspension, or absorption of many materials – including fine sediments, nutrients and chemical compounds – further adding to water's habitat forming capabilities (Hynes 1972). Acting together, these properties of water shape or set the template for many of the processes that form and determine the productivity of aquatic habitats.

Figure 1.0. Skykomish River, Snohomish County, Washington at Sultan in 1938 (top panel) and 2001 (lower panel). Dashed polygon areas in both panels illustrates dynamic floodplain forest succession (white) and floodplain forest erosion (black) over time.

The Role of Glaciers and Sediment

Glaciers set the stage for today's habitats (Beechie et al. 2001) in Snohomish County. They blanketed much of Puget Sound's landscape as recently as ten to fifteen thousand years ago and, as they receded from the lowlands, created the initial shape of the landscape seen today (Downing 1983; Booth 1994; Beechie et al. 2001).

In many parts of the County, glacial valleys (e.g, Sauk River, Stillaguamish River, Skykomish River) were filled with sediments through which streams incised rapidly, forming terraces and lowering and narrowing floodplains (Beechie et al. 2001). As supply from sediment-filled valleys, in combination with new surficial erosion, was transported downstream, deposition and natural variation in flooding created anastomozing channels, lateral migration, and an abundance of side channels (see Figure 3.0). Elsewhere, the unstable bluffs along much of the Puget Sound nearshore and the region's river valley hillsides, steep ravines, shifting shorelines and meandering river channels are a direct result of the actions of glaciers. These features and the dynamic erosional processes they encompass, while sometimes dangerous to buildings and structures in their path (Gerstel et al. 1997; Palmer 1998), are the source of sediments which, when delivered at natural rates and magnitudes, replenish and rejuvenate aquatic habitats (Benda et al. 1992).

Glaciers also left an array of less dynamic but equally important features, including extensive till and outwash-based plains, containing springs, lakes, ponds, bogs, and fens. Some of these features, such as springs and especially bogs and fens, are uniquely adapted to the highly stable post-glacial conditions in which they formed. As a result they are highly susceptible to subtle changes in the rate and magnitude of water and sediment delivery (Kulzer et al. 2001).

Glaciers also greatly influenced soils (Gerstel et al. 1997). In some cases, receding glaciers left highly compressed surface soils, called till, with relatively low water permeability (although usually far more permeable than paved surfaces) that resists groundwater recharge. In other cases, glaciers left well-washed, highly permeable gravel and coarse sand deposits called outwash. Often, this surficial geology was layered, with recessional outwash overlaying till overlaying advance outwash. Thus, the science indicates that the complexity of surficial geology and the type of soils within a catchment heavily influences the hydrology of aquatic areas (Booth et al. 2003). Streams draining areas with high levels of till will have faster runoff and flashier flows than those dominated by glacial outwash (Booth et al. 2003). Conversely, those streams with outwash areas will be the beneficiary of greater groundwater recharge as areas of storage, which will discharge water gradually over periods of dry summer months.

The Role of Forests

Following glaciation, land was stabilized and hydrology moderated by coniferous-based forests that became established in coastal areas of the Pacific Northwest. These forests were comprised of some of the largest trees and highest vegetation biomass of any ecosystem on earth (Franklin 1988). Where those forests remain intact, their canopy, understory, accumulated organic matter and surface soils intercept and store the vast majority of storm precipitation and subsequently meter it out gradually to aquatic habitats and underlying aquifers. The type and amount of vegetation, both riparian and upland, combined with the storage potential described, tempers the erosive energy of water as well as the rate of sediment scour and transport (Gordon et al. 1992). In addition to its hydrologic influence, forest vegetation serves as a source of nutrients upon which other plants and animals thrive. It is also important in water, sediment and nutrient storage and cycling, and helps create structurally and functionally diverse aquatic habitat (Gordon et al. 1992).

Dead and down woody vegetation (woody debris) of all species, shapes and sizes accumulates, sometimes in huge quantities, on the forest floor as well as in streambeds and estuaries and along lake and marine shorelines. Prior to modern development, large amounts of large woody debris were extensively distributed along marine shorelines, estuaries, and rivers (Maser et al. 1988; Bilby and Bisson 1998; Collins and Montgomery 2002; Collins et al. 2002). In some cases, the size and volume of the woody debris was sufficient to create logjams that spanned rivers as large as the Skagit (Sedell et al. 1989). Note that in Figure 3.0, the floodplain forest (dashed black polygon in 1938 photo) has been completely replaced by gravel bar and the mainstem channel, while at another location (dashed white polygon) floodplain forest has developed to stabilize gravel bars and provide habitat functions to a remnant side channel.

Large and small woody debris interacts with water and sediment to create localized sediment scouring and deposition, and results in more complex, and in many cases, more stable habitat than would occur in the absence of such material (Sedell and Beschta 1991; White 1991; Montgomery and Buffington 1997; Heede 1985; Jackson and Sturm 2002; Ralph et al. 1994; Beechie and Sibley 1997; reviewed in Roni et al. 2002). In streams, woody debris generated pools and riffles provide habitats for migration, spawning, rearing, and refuge from periodic disturbances, such as major storms or landslides. In marine nearshore environments, woody debris diffuses the energy of tides and waves, thereby modifying on-shore sediment transport and helping to create habitats ranging from muddy bays to gravel or bedrock beaches. In all aquatic environments, including lakes, ponds and estuaries where water energy is very low, woody debris increases the amount, diversity, and quality of cover needed for resting, foraging, and predator avoidance.

The Role of Animals

In addition to water, glaciers, and forests, aquatic animals themselves can play a major role in the structure and functioning of their habitats and ecosystems. Beavers (*Castor canadensis*) and Pacific salmon (*Oncorhynchus spp.)* are perhaps the best examples of aquatic animals in the Pacific Northwest that modify their own environments, often with profound, far-ranging effects. Beavers, which were once much more abundant than they are today, dam extensive segments of small stream channels and riverine valley floors altering flow and sediment deposition patterns and creating considerable habitat for plant and animal species such as willow (*Salix* spp) and coho salmon (*Oncorhynchus kisutch*), respectively (Naiman et al. 19; Beechie et al. 1994; Murphy et al. 1989; Snodgrass and Meffe 1998; Leidholt-Bruner et al. 1992). Pollock et al. (2003) found documentation of use of beaver ponds as habitat by more than 80 species of fish, 48 of which commonly used them. Beaver ponds create highly productive slow water with high-vegetated edge-to-surface ratios and extensive cover. As a result they typically harbor more and larger fish than unponded areas (Murphy et al. 1989; Leidholt-Bruner et al. 1992; Schlosser 1995). In addition to fish, beaver ponds have been shown to be productive habitats for many birds, mammals, plants, and insects (Naiman et al. 1988).

Salmon, especially when returning in large numbers, can reshape substantial areas of stream and, in some cases, near-shore substrates by loosening gravels during excavation of their nests, and in the process improving spawning substrates by releasing fine sediments and organic matter, which could interfere with continuous oxygenation of their embryos (National Research Council

1996; Quinn and Peterson 1994). They also deposit large amounts of marine-derived nutrients that boost aquatic food chain productivity and survival of their juveniles as well as nourishing many other plants and aquatic and terrestrial animals (Cederholm et al. 1989; Bilby et al. 1996; Cederholm et al. 1999; Wipfli et al. 2003). Consequently, the science indicates that these and many other species play an integral role in the function of aquatic habitats.

Natural Cycles of Change and the Role of Disturbance

As described above, the type, amount, and condition of aquatic habitats reflect a complex, dynamic interplay of water, soil, plants, and animals (Ward and Stanford 1995), driven by global, regional and local climatic (temperature and rainfall) and geologic processes (earthquakes, volcanoes, soil formation, and transport processes) (National Research Council 1996). While the cycles may be gradual and subtle, the effect is sometimes dramatic, in the form of floods, fires, and droughts and, at much longer intervals, volcanoes, and ice ages. These periodic events are referred to as "disturbances." Although these events may be catastrophic when people, homes, or property are affected, they are important for the functioning of an ecosystem and for the persistence of many species (Reice 2001). The frequency and magnitude of these events over time define a region's disturbance regime and act to form the natural habitats to which native species are adapted (Ward and Stanford 1995; Beechie and Bolton 1999).

Regardless of how or why they occur, such environmental perturbations have favored the evolutionary survival of plants and animals with life history strategies that enable them to cope with and to some extent thrive on disturbance (Reeves et al. 1995; Independent Multidisciplinary Science Team 2002). Natural disturbances periodically reshape and rejuvenate the landscape and its habitats. For example, regional climatic cycles of warming or drying may culminate in intense and widespread fires (Agee 1997), which in turn are important for the propagation of certain plants and animals. Additionally, periods of increased moisture may lead to greater frequency and intensity of storms resulting in periods of greater flooding and erosion (Swanson et al.1982; Independent Multidisciplinary Science Team 2002), all within the range of normative flows, but which can lead to improved riparian vegetation condition and spawning and rearing habitat condition for fish (Poff et al. 1997).

Channel Migration and Shoreline Erosion

Stream channel migration and shoreline erosion are processes that are important for creating and sustaining healthy, diverse habitats. In large part, they are ecological processes driven by disturbance regimes, such as floods and cycles of freezing and thawing, which contribute alluvial sediments, spawning gravel, woody debris and nutrients that sustain and invigorate existing habitats, create new habitats, such as side channels and oxbow ponds, where none previously existed, or fill in old, less productive habitats. In less dramatic ways, these processes also result in lateral scouring along banks and shorelines creating pools and riffles in stream channels and diverse habitats within floodplains and along marine, estuarine and lake shorelines (White 1991).

Areas affected by channel migration, the movement of a river or stream channel across its valley bottom, are called Channel Migration Zones (CMZs). There is no specific correlation between the extent of the CMZs and areas of flood inundation. The area within a CMZ may extend beyond the 100-year floodplain, or the 100-year floodplain may extend beyond the CMZ. Given time and without obstruction, a natural, unimpeded, meandering channel can swing and shift across its valley and the entire pattern may sweep downstream, resulting in a complete reworking of the alluvial floodplain (Schumm 1977). It is the floodplain that is an integral part of the river ecosystem. Complex floodplains are formed where unconfined river systems receive periods of seasonal flooding. Flood events of different size and frequency are important in maintaining a diversity of riparian plant species and aquatic habitats such as side channels, oxbow lakes, wetlands, and diverse forest communities (Junk et al. 1989; Gregory et al. 1991; Naiman and Bilby, 1998). Biological productivity is often enhanced in floodplains because sediment and nutrients are deposited during periods of flooding (Bayley, 1995) and accessibility to these habitats affords greater foraging benefits (Junk et al. 1989; Sommer et al. 2001). As well, input of larger organic material (such as Large Woody Debris (LWD)) and the establishment of pioneer plant species (Gregory et al. 1991; Naiman and Bilby, 1998; Naiman et al. 2000) accompanies channel migration and deposition of eroded sediments.

As sediment and LWD are transported and deposited throughout the stream system, channel geomorphology is affected and aquatic habitat features are formed. Woody debris accumulations appear integral to formation and maintenance of an anastomosing (i.e., branching and recombining) channel pattern (Abbe and Montgomery 2003) for maintaining multiple channel morphology, and regulating flow from main channels to perennially flowing floodplain sloughs (Collins and Montgomery 2002), which are known to offer productive habitat for salmon (Beechie et al. 1994). Thus, the science leads to the conclusion that LWD is important because it influences the routing of water and sediment in streams with abundant LWD and/or beaver activity (Pollock and Kennard 1998). At the same time it is known stable LWD structures can resist channel migration, forming a revetment that halts local bank erosion, often altering the orientation of flow relative to the jam. Stable LWD jams that persist long enough to be buried in a floodplain are associated with anomalous forest patches older than the surrounding floodplain forest (Abbe and Montgomery 1996), indicating long-term resistance to lateral erosion.

Recognition of the ecological and erosional role these processes play and the hazards they represent to people have resulted in the designation and regulation of CMZs along rivers and protective setbacks along eroding bluffs and beaches of Puget Sound. But much historic development has occurred in these areas. As a result, habitat-forming processes have been greatly reduced or lost along many of Snohomish County's rivers and shorelines. In turn, this has contributed to a significant loss of habitat quantity and quality (e.g., Haas and Collins 2001). For example, in a study of the Snohomish River estuary, it was estimated that the combination of near continuous diking, riparian clearing and wood removal has reduced the historic marsh area by 83% and the historic blind tidal slough area by 75% (Haas and Collins 2001). In the Stillaguamish River, off channel habitats (distributary sloughs and ponded areas) have been isolated, filled, or reduced in their potential to support coho salmon production by 90% (Beechie et al. 2001).

Examples of Integrated Ecological Models and Use and Applicability of Indicator Species

To integrate knowledge about ecosystems into a common framework and to guide research and management, scientists have constructed a variety of models that describe how freshwater and marine habitats work and the relative importance of various physical, chemical and biological processes as they affect indicator species. For riverine systems, the dominant model is the River Continuum Concept (RCC) proposed by Vannote et al. (1980). The complimentary model for marine nearshore habitats is that of Intertidal Zonation as initially described by Ricketts and

Calvin in 1939 and later substantially revised by Phillips et al. (1985). These two models are described briefly below. The use and applicability of indicator species is particularly important with respect to understanding how species and habitats they rely on are affected by human induced changes to critical areas and how uses in or near critical areas may be evaluated and regulated.

The River Continuum Concept (RCC)

The RCC holds that the distribution of stream characteristics reflects a headwater-mouth gradient of physical conditions that affect the biological components in a river including the location, types, and abundance of food resources relative to stream order. Some of the key features of the concept are shown in Figure 3.1 and summarized in Table 3.0.

The influence of riparian and landscape factors varies depending on stream size. For example, small to medium-sized, forested streams have relatively large inputs of terrestrially derived plant matter (e.g., leaf litter and wood) and woody debris from surrounding riparian and upland areas compared to high-order (larger) river systems. The productivity of smaller streams is more dependent on riparian vegetation for their nutrients than larger streams, which are dominated by primary production (e.g., algae growth). Similarly, the temperature regime of small headwater streams is much more strongly influenced by vegetative shading than that of large streams.

More recently, it is being recognized that considerable variation in processes and distribution of resources (sediment, woody debris, and animals) occurs in the context of the continuum. For example, Brussock and Brown (1991) showed that simple alternating pool:riffle streambed morphology creates discontinuities in substrate conditions and invertebrate abundance. Similarly, Osborne and Wiley (1992) showed that tributary junctions affected the distribution of fish species. And Benda and Dunne (1997) describe the discontinuous nature of sediment as it is routed through a stream system. The variation in processes and distribution of resources (physical, chemical, and biological) has also been extended to the floodplain and is known as the flood-pulse concept (Junk et al. 1989). This concept emphasizes the role of disturbance events (floods) that connect the floodplain (off-channel habitats) and the main river channel together such that the abundant nutrient resources, unique habitats and refugia, and physical, chemical, and biological processes are available to instream biota (e.g., Peterson and Reid 1984; Swales and Levings 1989; Sommer et al. 2001). In Snohomish County, this is best exemplified by the access and use, by coho salmon in particular, of off-channel over-wintering habitats (side channel sloughs, beaver ponds, oxbow channels) during rain and snowmelt dominated flood periods (Beechie et al. 2001). The importance of the flood-pulse concept varies within the context of the RCC. In higher order, low-gradient, large floodplain rivers the flood-pulse concept is relatively more important than in low order, higher gradient streams without well-developed floodplains (Ward and Stanford 1995).

In addition to discontinuities and disturbance events affecting the longitudinal profile of streams and rivers and lateral extent of these perturbations, a third dimension extends vertically and radially into the hyporheic zone, the shallow unconfined aquifer of highly permeable sediments where surface and groundwater mix, dissolved nutrients, organic matter, and other water quality constituents exchange, and riparian vegetation contacts to support growth and survival in hot dry summer months. The hyporheic zone represents a unique microhabitat for a diversity of aquatic insects and other microorganisms affecting biological processes such as denitrification and the storage of particulate organic matter (Stanford and Ward 1988).

Thus, the role of discontinuities and disturbance, (e.g., tributary junctions, braided areas, logjams, debris flows, and floods) in creating diverse habitat patches and uneven distributions of species and watershed processes is now understood to contribute to the complexity of stream ecosystems (i.e. Junk et al 1989; Ward and Stanford 1995; Fausch et al. 2002).

Figure 3.1 River Continuum Concept

Changes in aquatic communities from small streams to large rivers in the McKenzie River (Oregon) drainage, illustrating the River Continuum Concept. CPOM and FPOM, as shown are Coarse Particulate Organic Matter (>1mm) and Fine Particulate Organic Matter (5µm-1mm), respectively. Pie charts show how abundance of four different types of aquatic insects feeding guilds (collectors, predators, shredders and grazers) vary from headwater to large streams (Vannote et al. 1980).

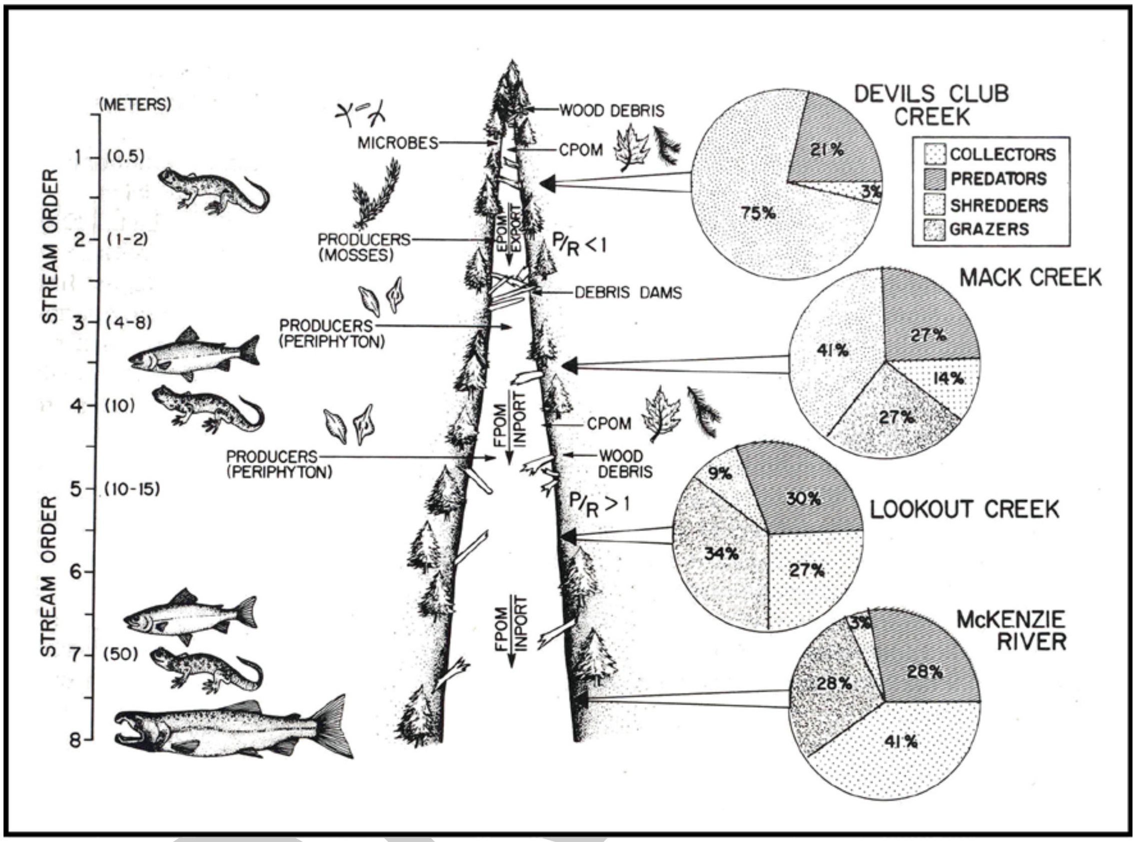


Table 3.0. Summary of the features important in the River Continuum Concept adapted from Vannote et al. (1980).

Feature	Generic Headwater Stream	Generic Mid-Sized Streams	Generic Large Rivers
Stream Order	1-2	3-5	6-9
Channel	Confined	Moderately Confined	Wide
Riparian Growth	Dense (stream channel covered at least part of year)	Moderate (majority of channel exposed)	Low (only stream margins covered; organic input is minimal)
Shading	High	Moderate to Low	Low
Substrate	Boulder, cobble, and gravel	Generally cobble and gravel	Gravel, sand, and silt
Water Temperature	Low and stable	Highly variable	High and stable
CPOM-Coarse Particulate Organic Matter	High (input from riparian growth)	Moderate (from upstream and little new input)	Low
FPOM-Fine Particulate Organic Matter	Low	High (flowing from upstream and produced here)	High (flowing from upstream and produced here)
Primary Production	Low (low algal growth due to little direct light)	High (high algal growth due to direct light and low turbidity)	Low (low algal growth due to insufficient light and substrate conditions)
Shredders	High	Low	Low
Collectors	High	High	High
Grazers	Low	High	Low
Predators	Low	Low	Low

Functions of headwater streams

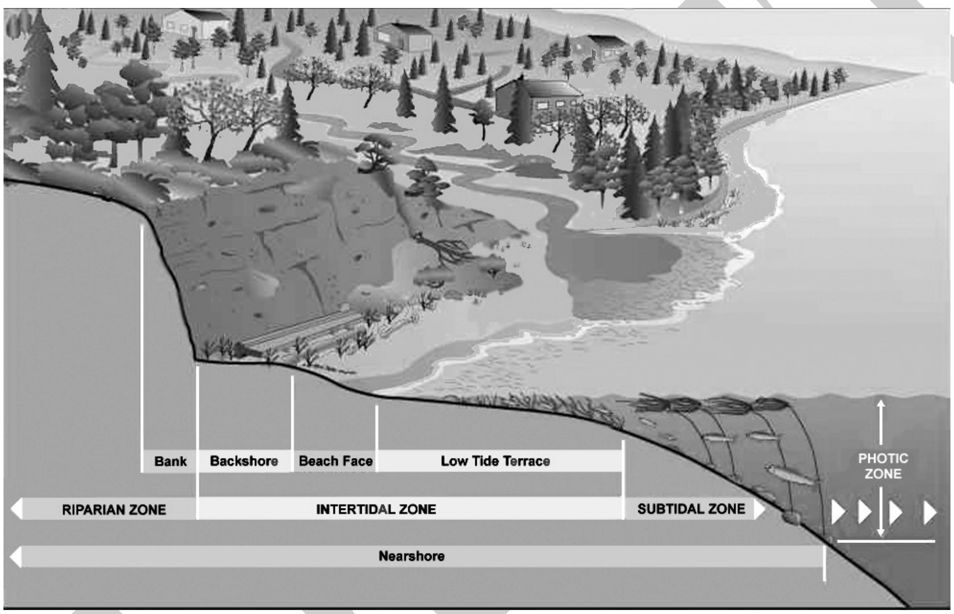
Headwater streams (1st and 2nd order) play an important role in stream ecosystems. Typically, they make up most of the stream length within a watershed (Benda et al. 2004). They also can heavily influence downstream habitats and often contain some of the most sensitive (albeit not necessarily the most abundant or productive) stream species, including bull trout, Pacific giant salamanders and tailed frogs (Bisson et al. 2002; Raphael et al. 2002). They are often situated among the most steep and sensitive slopes making them susceptible to landslides, which can contribute to extensive destabilization of downstream areas. However, as previously discussed, landslides and other natural disturbances are not necessarily bad. When they occur at natural rates and magnitudes they deliver woody debris and sediments, including spawning gravel, which help downstream reaches to function properly.

Functions of fishless and isolated aquatic areas

Some aquatic areas have no fish or fish-bearing potential. For example, Latterell et al. (2003) found that absent impassable barriers, salmonids were rarely found in small streams at gradients greater than 22 percent. In some cases, small streams originating as spring seeps go underground before making a surface connection with a fish-bearing aquatic area. In other situations lakes and ponds having no surface connection to a fish-bearing stream or have waters that are unsuitable for fish (e.g., bogs are too acidic). Regardless, isolated or otherwise fishless isolated waters can be used extensively by other animals, especially amphibians and macroinvertebrates (e.g., stoneflies) for breeding, rearing, or refuge (Muchow and Richardson 2000). When they disappear due to infiltration, their waters can contribute to local aquifers that ultimately supply fish-bearing waters with cool, clean groundwater. Thus, fishless and isolated waters can function as habitat for non-fish species and indirectly provide for the water quality and hydrologic functioning of waters with fish.

Similar to rivers, habitat and species use along marine shorelines occur in gradients that are determined by fluctuations in currents, water level (tides), geologic and sediment substrate conditions, water quality, and salinity. The Intertidal Zonation model (Figure 3.2) accounts for many of these factors using zones occurring vertically between the upper extent of marine water influence and the photic zone, which extends down to the depth at which rooted photosynthetic plants, such as Giant Kelp, exist.

Figure 3.2 Illustration of the Marine Intertidal Zonation concept



Zones are generally delineated into one of four categories: the spray, high intertidal, low intertidal and subtidal zones. Steep, unprotected shorelines composed of large boulders or bedrock will have a different set of habitats and species than shorelines at the base of actively eroding, sandy banks with a gradual slope. For example, barnacles generally do not occur in the low intertidal and subtidal zones or in areas without large substrate. This is due to predation by numerous other organisms and the need to adhere to something stable. They have adapted to life in the harsh transition area between the terrestrial and marine environments, where predation is much lower and exposure to the sun and air is much greater. Whereas, species like sand dollars and eelgrass occur in the low intertidal and subtidal zones. They are unable to live in the higher zones since they can not be out of water for extended periods of times like barnacles. They are also found only in areas with sandy substrates. Proximity to large rivers and streams also changes the water quality (turbidity, salinity, temperature), which can cause similar looking marine nearshore environments to have substantially different plant and animal communities.

Another factor shaping marine and estuarine shorelines that is not illustrated well within the intertidal zonation model is the horizontal, along-shore affects of currents, waves, and winds. Drift cells are systems in which sediment is suspended by waves or currents and transported along the shoreline in a repetitious cycle of suspension and deposition. Essentially, they are the mechanism that supplies marine nearshore environments with the majority of the sediments that form beaches, sand and mud flats, and maintains rarer features like sand spits and their associated marshes. Also, marine offshore/deepwater areas extend beyond subtidal areas to the westernmost Snohomish County jurisdictional boundary. These areas support a number of species including migrating salmonids, Pacific herring stocks, whiting (hake) stocks, Dungeness crab, and pandalid shrimp.

Salmonids as Ecological Indicators and Keystone Species

Salmonids (e.g., salmon, trout, and char) are of particular interest in Snohomish County as well as throughout the Pacific Northwest because of their cultural, social, political, legal and economic importance (National Research Council 1996). They are also important ecologically, as they are the region's most diverse family of freshwater and anadromous fishes. Their distribution in aquatic habitats is very broad as some species (cutthroat and rainbow trout) can be found in small ephemeral streams with gradients as steep as 22 percent (Latterell et al. 2003). Ocean-going (anadromous) forms bring nutrients from highly productive marine areas to otherwise nutrient-poor freshwater streams and riparian areas when they return to spawn (Willson and Halupka 1995; Naiman et al. 2002). An unknown number of aquatic invertebrates and 137 species of birds, mammals, amphibians, and reptiles have been found to be predators or scavengers of salmon at one or more stages of the salmon life cycle (Cederholm et al. 2000). In some cases, they spawn in sufficient numbers that their digging action modifies the shape of streams and in the process cleans sands and silts from stream substrates (Cederholm et al. 1999). For these reasons, salmonids are considered keystone species and are a commonly used benchmark for setting protection standards and assessing the effectiveness of aquatic habitat protection and restoration measures.

Compared to other fishes in Snohomish County, salmonids exhibit exceptionally high life history diversity both within and among species. Although they overlap considerably in their distribution, each species and life history variation presumably has arisen in adaptation to specific aspects (flow, gradient, size, temperature, presence of other species) of the dynamic and complex aquatic habitat found in our region. Regionally, among all counties, Snohomish County is host to the greatest number of independent populations of threatened Chinook salmon (NOAA 2001). Some species (e.g., Chinook salmon) are adapted to spawning in rivers and larger tributaries, while others (e.g., cutthroat trout and coho salmon) reproduce in smaller streams. The juveniles of some species (e.g., steelhead) prefer rearing in very fast water; others (e.g., coho) do best in slow areas such as beaver dams or backwater ponds or, as with sockeye, large lakes. Some species, such as bull trout, require the coldest and often access to the highest elevation streams possible for spawning and early rearing, and others, pink and chum salmon, tend to be found primarily in the lowermost reaches of streams.

Where they have access to saltwater, most salmonid species are anadromous – they spawn in freshwater, then, after a variable amount of time migrate into, grow, and mature in marine waters, ultimately returning a year or more later (depending on the species) to their natal streams as larger, mature individuals. In contrast, resident forms spend their entire life history in freshwater. Some residents migrate very little, spending the majority of their life within a relatively small reach of stream usually limited by a natural barrier, such as an impassible falls or cascade. Other resident forms are referred to as either fluvial or adfluvial, meaning they migrate extensively within a river or river-lake system, respectively.

Anadromy is an especially important life history strategy for salmon. It allows access to highly productive ocean environments, improving the growth and reproductive potential for those individuals and populations using this strategy. It also allows for transport of significant amounts of nutrients from the ocean to natal streams and riparian areas. Freshwater streams of Puget Sound tend to be naturally low in nutrients, thus these nutrients benefit the fish's offspring and many other plants and animals (Cederholm et al. 1999; Naiman et al. 2002). Because of their migratory behavior and near-ubiquitous presence in Puget Sound streams and shorelines, salmon are food or nutrients for a wide host of other plants and animals. From the perspective of habitat management, anadromy complicates our understanding of the role of local (Snohomish County and smaller watersheds) habitat and development impacts because conditions outside Snohomish County are a major factor in controlling the abundance and productivity of ocean-going salmon populations. This factor adds to the difficulty in understanding relationships between local habitat conditions and development impacts.

Salmonids population levels are affected by development and are potentially valuable indicators of change. Lucchetti and Fuerstenberg (1993) and Ludwa et al. (1997), found fish species diversity declined with increasing levels of urban development, and that cutthroat trout (*Oncorhynchus clarki*) became the dominant salmonid species (sometimes the only remaining fish species) in small streams draining heavily urbanized catchments in the Lake Washington watershed (south Snohomish County). Pess et al. (2002) found adult coho salmon (*O. kisutch*) densities in the Snohomish River basin to be correlated with wetland occurrence, local geology, stream gradient, and land use. They also found median densities of coho spawners in forest-dominated areas were 1.5 to 3.5 times the densities in rural, urban, and agricultural areas. Furthermore, they found that forested areas maintained positive correlations with spawner abundance, whereas those converted to agriculture or urban uses had negative correlation with spawner abundance. Moscrip and Montgomery (1998) found systematic declines in salmon abundance in Puget lowland streams (including Swamp Creek) related to changes in flood frequency (more frequent and flashier flows) caused by urbanization.

In Oregon and Washington, Roni and Quinn (2001) found that adding large woody debris to small streams (four to 12 meters in bankfull width[1]) impacted by land uses (mostly forestry) can lead to higher densities of coho during summer and winter, and higher densities of cutthroat and steelhead during winter. May et al. (1997) found that the ratio of coho to cutthroat trout was a good correlate of habitat impact. Even when a salmonid species persists in the face of development-induced habitat changes and may appear healthy based on abundance, there is concern that the *diversity* of the species' life history, and thus the science indicates that the health of the species, is much reduced due to loss or modification of habitat complexity.

Finally, it should be recognized that in addition to marine and freshwater habitat conditions, many salmonids are heavily affected by commercial, sport, or subsistence fisheries and hatcheries, which are used to restore or increase these fishing opportunities (National Research

[1] Bankfull width is the lateral extent of water surface elevation at bankfull depth; bankfull depth is water surface elevation required to completely fill the channel to a point above which water would spill onto the floodplain (Water Typing, Bankfull Width, and Channel Migration Zones, DNR).

Council 1996). Hatcheries tend to cause domestication, reduced genetic fitness, competition, and disease risk to naturally spawning populations (Reisenbichler 1997, Waples 1999). When not properly managed, fisheries and hatcheries tend to reduce the productivity and abundance of wild populations (Sweeting et al. 2003).

Other Species as Indicators of Ecological Health and Change

Many other plant and animal species beyond salmonids contribute to the overall aquatic habitat functions and biodiversity of Snohomish County. Their requirements are not necessarily the same as for salmonids and some may be better indicators because they are less mobile and have less tolerance for change. Good examples are amphibians such as the Pacific giant salamander (*Dicamptodon tenebrosus*), tailed frogs (*Ascaphus truei*), which use very small, steep streams and seeps that may have little or no potential for salmonid use.

In a study of small, mostly steep headwater streams of the Olympic Peninsula, Bisson et al. (2002) concluded that stream-dwelling amphibians were more influenced by riparian and watershed conditions and fish were more strongly influenced by in-stream habitat conditions. They conclude that the fish were probably responding to frequent disturbance events, such as landslides that modify in-stream habitat, whereas the amphibians were responding more to watershed level changes in forest cover that alter hydrology and water quality. Using the same study of streams, Raphael et al. (2002) concluded that in-stream and near-stream amphibians were better indicators than fish, birds or mammals of stream and stream-side habitat condition, probably because of their low mobility, tendency to reside in or return to specific locations, lengthy larval period, ability to populate beyond obstacles to movement, and narrow limits of environmental tolerance.

Aquatic mollusks (e.g., western pearlshell mussel, *Margaritifera falcata*) are another class of animals that can be indicators of change. For freshwater habitats, they have been noted as being good measures of environmental change as they can be sensitive to changes in water quality and fine sediments (Fevold and Vanderhoof 2002). As with amphibians, they are also relatively immobile and therefore cannot avoid changes in environmental conditions.

Finally, Karr and Chu (1999) discuss the use of benthic invertebrates (insects, crustaceans, and mussels) and fish in the development of indices of biotic integrity (IBI). The IBI evaluates the presence and abundance of pollution tolerant and pollution intolerant species to gauge the biological effect of pollution and other changes. Originally developed using fish species in the Midwest, an area that has a high diversity of fishes, the IBI was altered for Puget Sound streams to use benthic invertebrates (hence, the B-IBI) to improve the discriminatory capabilities of the index because the Pacific Northwest has a relatively low diversity of fish species. Measures of B-IBI from the Puget Sound region have been shown to be well correlated with watershed conditions of total impervious area (Booth et al. 2002), road density and frequency of road crossings at streams (Alberti et al. 2005), and measures of hydrologic alteration, such as T_{Qmean} (the fraction of a year that the daily mean discharge exceeds the annual mean discharge, Booth et al. 2004). B-IBI has also been shown to be correlated with local (on site or within 1 km upstream) stream channel conditions (McBride 2001), local (near-stream) urban land cover (Morley and Karr 2002) and a qualitative riparian and instream habitat index (May et al. 1997). Thus, the best available science leads to the conclusion that the B-IBI is sensitive to both factors that impact riparian and aquatic habitats and functions and factors that have mitigative value (Horner et al 2002).

Existing Conditions of Aquatic Areas and Contributing Watersheds

In Snohomish County, existing conditions of aquatic areas (specifically, wadable streams, non-wadable large rivers, estuaries and marine nearshore areas (wetlands are covered in Chapter 5) have been documented based on quantitative and qualitative surveys. In some cases, the information resources are comprehensive related to the habitat requirements of salmonids and span multiple years of investigation. The variability in condition of aquatic areas and biological responses to the range of conditions present (suitable to highly degraded) is explained in part based on the condition of the contributing watershed area particularly with respect to land cover (i.e., forested, impervious, pastured areas, etc.), which has been well documented over the past decade (Purser et al. 2003). Source documentation of existing conditions in Snohomish County for contributing watershed area and aquatic habitats are included in Table 3.1 below. These documents as cited also contain supporting references, both qualitative and quantitative, that the reader may refer to.

Table 3.1. Selected source documentation summarizing existing conditions in Snohomish County for contributing watershed areas and aquatic habitats.

Scale/ Subscale	Characterization	Year	Sources	Evaluative Criteria	Citation
Watershed (WRIAs 5,7,8)/Subbasins	Land cover (12 classes), whole basin and nearstream (≈300ft)	1991, 2001	Landsat imagery	No	Purser et al. 2003
Watershed (WRIA 5)/Subbasins	Habitat Limiting Factors	2000, 2002	Various	Yes, NMFS 1996, WFPB 1997, others	WCC 1999, STAG 2000, STAG 2002
Watershed (WRIA 7)/Subbasins	Habitat Limiting Factors	2002	Various	Yes, NMFS 1996, WFPB 1997, others	SBSRTC 2002; Haring 2002
Watershed (WRIA 8)/Subbasins	Habitat Limiting Factors	2001	Various	Yes, NMFS 1996, WFPB 1997, others	Kerwin 2001
Large River -Stillaguamish Snohomish, Skykomish, Pilchuck rivers/ Main channel, side channel	Geomorphic units (pools, riffles), bank conditions, large woody debris and jams	2002, 2004	Haas et al. 2003. Appendix E, SCSWM (2002d)	Yes, NMFS 1996	Haas et al. 2003
Wadable Streams (22 subbasins including Drainage Needs Reports)/ Main channel, side channel	Geomorphic units (pools, riffles), bank conditions, large woody debris and jams, fine sediment, qualitative riparian assessment, BIBI	2000-2002	SCSWM (2000, 2002b)	Yes, NMFS 1996, WFPB 1997, others	SCSWM (2001, 2002a, 2002c 2003a)
Snohomish County Marine Shore Inventory/ Upper intertidal, littoral, and riparian	Shore zone units, of riparian condition, drainage features, bank condition and armoring,	2002	In preparation	No	

WRIA – Watershed Resource Inventory Area

NOAA – National Oceanic and Atmospheric Administration, home of NOAA-Fisheries, formerly known as National Marine Fisheries Service (NMFS)

WFPB – Washington Forest Practices Board

STAG – Stillaguamish Technical Advisory Group

SBSRTC – Snohomish Basin Salmon Recovery Technical Committee

SCSWM – Snohomish County Surface Water Management

Riparian Areas Functions and Relationship to Aquatic Areas

Natural riparian corridors provide an extremely wide range of highly valuable functions to aquatic areas, proportionately more so than upland areas (NRC 2002). In addition to being important habitats in their own right for a wide range of wildlife (Knutson and Naef 1997), they are also considered essential for sustaining wild fish populations (Naiman et al. 1993; May et al. 1997). Naiman et al. (1993) notes that riparian areas are the most diverse, dynamic, and complex biophysical habitats on the terrestrial portion of the Earth. The Puget Sound area's wild salmonids are adapted to thrive in forest-lined fresh waters during significant parts of their life cycles and depend on the riparian system's diversity, dynamism, and complexity. There is no known suitable, long-term substitute for healthy riparian forests and research indicates that riparian buffer protection, land use controls, and stormwater management programs in combination may form the best approach to protect these habitats functions and values (May 2000; Horner et al. 2002; Booth et al. 2004).

Gregory et al. (1997) stated that before the widespread removal of riparian forests in the Northwest's lower valley floodplains, the forests were critical for moderating the effects of winter floods and summer and winter temperature extremes by providing refugias, particularly along secondary channels and off-channel ponds (Peterson and Reid 1984; Brown and Hartman 1988; Swales and Levings 1989). Pollock and Kennard (1998) point out that "riparian buffers are the key component of any salmonid habitat conservation strategy because they provide the majority of the ecological goods and services required to keep salmonid habitat functional."

Protection of Puget Sound's native salmonids is aided by the presence of healthy riparian forests. In their natural state, riparian areas are generally dominated by coniferous trees, usually Douglas fir, western hemlock, and western red cedar (Brosofske et al. 1997; May 2000) but a certain portion are in less advanced stages of succession due to disturbances, and may be dominated by other woody species such as alder, cottonwoods or maples, or perhaps even meadows. The result is a complex array of riparian habitats contributing to the species diversity of an area.

Many species compose the native riparian plant communities. Some riparian vegetation is characterized as *obligate*, for species growing only in riparian areas, and some as *facultative*, for species commonly occurring there but also in upland terrain. Obligate riparian plants tend to depend on a high water table, tolerate inundation and soil anoxia, tolerate physical damage from floods, colonize flood-scoured surfaces, and colonize and grow in substrates having few soil nutrients (Naiman et al. 2000; Rot et al. 2000).

In summary, healthy riparian zones are living, ever-changing systems, often subjected to natural disturbance (flood, drought, fire, landslide, insect infestation, etc.), then responding via successional pathways. These dynamic riparian ecosystems perform various functions that form salmonid habitat. Below are descriptions of some of the commonly cited major functions.

***Producing and delivering large and small woody debris (LWD and SWD) to shorelines and stream channels*.** LWD and SWD are important because it affects the routing of sediment and water (Megahan 1982; Montgomery and Buffington 1997), as well as streambed topography and stability (Keller and Swanson 1979; Lisle and Kelsey 1982; Bilby 1984; Heede 1985; Abbe and Montgomery 1996). LWD can dissipate stream energy through flow resistance, slowing erosion and sediment transport and retaining coarse particulate organic debris (Bilby and Likens 1980; Bilby 1981). LWD plays a key role in the development of riparian forests by routing and retaining sediments in floodplains or channel bars for vegetation colonization (Abbe and Montgomery 1996; Fetherston et al. 1995).

The important role of fallen trees and tree parts as structure-forming elements in stream channels is well known (Leinkaemper and Swanson 1987), especially related to pool formation (Harmon et al. 1986; Bisson et al. 1987; Leinkaemper and Swanson 1987; Andrus et al. 1988; Bilby and Ward 1989; Robison and Beschta 1990; Bilby and Ward 1991; Fausch and Northcote 1991; Montgomery et al. 1995; Beechie and Sibley 1997; Bilby and Bisson 1998). Major salmonid habitat benefits of woody debris are apparent (Bustard and Narver 1975; Tschaplinski and Hartman 1983; Bisson and Sedell 1984; Sullivan et al. 1987; Rosenfeld and Huato 2003). The complex, submerged structure formed by LWD and SWD (and roots of woody vegetation) provides flow refugia (McMahon and Hartman 1989) and essential cover in which salmonids conceal themselves from predators and competitors and find profitable feeding positions, as inferred from observations in natural streams (Fausch and White 1981) and experiments in a stream aquarium (Fausch 1984; Lonzarich and Quinn 1995).

Removal of riparian forest results in long-term reduction of LWD (McDade et al. 1990; Van Sickle and Gregory 1990) and SWD (Bilby and Ward 1991) in streams. LWD deprivation leads to adverse changes in channel forming processes (Bilby 1984; Bisson and Sedell 1984), and a decrease in local salmonid production (Bryant 1983; Dolloff 1986; Fausch and Northcote 1992). Reduced LWD is deemed a major reason for salmonid decline in Pacific Northwest streams (Bisson et al. 1987; Sedell et al. 1989; FEMAT 1993; Stouder et al. 1997; Naiman and Bilby 1998).

Another of the important functions of LWD in streams is that it traps, accumulates, and retains smaller debris and other organic matter (Bilby 1981), including salmon carcasses (Cederholm et al. 1989). Woody debris in non-fish-bearing streams also benefits downstream salmonids by regulating sediment transport (Megahan 1982; Perkins 1989; Montgomery et al. 1996).

***Shoreline protection, bank stabilization, and habitat formation*.** The effectiveness of riparian vegetation is well known to naturally stabilize stream banks while providing structural habitat for salmonids. The vegetation also influences water current and shoreline shape in other ways that benefit salmonid habitat. As reviewed in Spence et al. (1996), roots bind streambank soils, and stems, branches, and projecting roots slow water currents that bear against riparian areas. The cover of healthy, native-plant communities generally perform this function more beneficially for salmonid habitat than do artificial reinforcements made of rock or other hard, non-living materials.

The riparian vegetation that protects shorelines also provides structural habitat for aquatic organisms, such as many salmonid microhabitats in live vegetation and in woody debris. This material, most important being tree roots and brush that drapes into the water, creates positions that are concealed from predators and give shelter from water velocity but are near fast currents that bring food (Fausch 1984). Vegetation resists shoreline erosion but generally not as drastically as do rock-riprap, concrete bulkheads, steel sheet-piling, and the like. Diverse native vegetation can be expected to moderately retard shoreline erosion while maintaining its dynamism, letting channels meander, thus forming and reforming salmonid habitat features. Reeves et al. (1995) described the dynamism of salmonid-producing ecosystems in the Pacific Northwest and put forth ideas for managing them so as to accommodate disturbance regimes.

Removing sediments and dissolved chemicals from water. Uptake of dissolved chemicals and filtration of sediments from overland-runoff and flood water is an important riparian function (Lowrance et al. 1984; Cummins et al. 1994). Spence et al. (1996) reviewed evidence for these processes and for alteration of the flux of these materials through stream systems and how they affect aquatic areas. Human activities in a watershed influence the flux and deposition of sediment in streambed gravels. For example, elevated levels of fine sediment in spawning gravels have been associated with timber-harvest activities, mining, grazing, urbanization and other human activities (May et al. 1997; Stouder et al. 1997). Also, fine sediment composition in Puget Sound streams was found to be correlated with the level of urbanization present (May et al. 1997). Literature analysis by FEMAT (1993) indicated that healthy riparian zones greater than 200 feet from the edge of the floodplain probably remove most sediment from overland flow. Any action, such as clearing, that degrades the integrity of the riparian zone will hamper its functions of chemical filtering, uptake, and of sediment deposition and storage for floodplain development.

Moderating water temperature. Thermal benefits of shading by riparian vegetation in summer are well described (Hall and Lantz 1969; Brown and Krygier 1970; Newbold et al. 1980; Beschta et al. 1987; Holtby 1988) and thermal regulation affects essentially all biological processes. Aside from summer cooling, riparian forest cover also exerts winter-insulating effects (Murphy and Meehan 1991). Spence et al. (1996) reviewed studies that elucidate riparian thermal benefits. The effectiveness of thermal shading depends on riparian vegetation composition, height, density, and the width of the stream channel as larger channels are less influenced by riparian shading. Beschta et al. (1987) report a minimum buffer width of 30 m regulates stream temperature in mature old growth forests in the Pacific Northwest. By extension, temperature regulation would likely not be achieved with a 30 m buffer of deciduous trees or shrubs as the composition or quality of the buffer is critical.

Providing favorable microclimate. Less obvious but perhaps no less important are the microclimatic influences of the riparian forest on air that passes through on its way to a stream or pond. These influences include humidity, temperature, and wind speed, as reviewed in Pollock and Kennard (1998). Brosofske et al. (1997) documented that riparian microclimate is important to consider in management because it affects plant growth, therefore influencing ecosystem processes such as decomposition, nutrient cycling, plant succession, and plant productivity. The microclimate of riparian areas is generally cooler in summer and warmer in winter than upland areas (Knutson and Naef 1997), creating diverse and favorable habitats for many species during these seasons (Knutson and Naef 1997). Thus, the science indicates that microclimate alterations can affect structure of the riparian forest, the waters within it, and the viability of many animals, including fish.

Providing habitat for terrestrial animals. Various animals that live in or frequent riparian zones are associated with salmonid populations. These include habitat modifiers, such as elk and beaver (Naiman and Rogers 1997), the former altering vegetation, the latter (Bustard and Narver 1975; Cederholm and Scarlett 1982; Murphy et al. 1989) making ponds, digging side channels, and altering vegetation. In addition, riparian-dwelling predators, such as otter and various birds, exert beneficial selective pressure on fish populations by removing weak or maladapted individuals. Predators and scavengers recycle nutrients from salmonid carcasses. These relationships are reviewed for Washington and Oregon in Cederholm (et al. 2000), which contains 576 references. A full discussion of riparian functions benefiting wildlife such as birds, mammals, and amphibians is discussed later in this chapter.

Providing proper nutrient sources for aquatic life. Riparian trees and other vegetation furnish water bodies with a "litter fall" of plant particles (leaves, pollen grains, etc.), as well as with terrestrial insects. These organic materials compose a major energy source for food webs that sustain production of salmonids, particularly in small (low- and mid-order) streams (Gregory et al. 1991; Naiman et al. 1992; Cummins et al. 1994). Along smaller stream channels, litter fall from healthy stands of riparian vegetation (an allochthonous source) is a relatively more important basis for the aquatic food web than within-channel (autochthonous) production of algae, which tends to predominate as the basis for the aquatic food web in wider, less shaded streams and in standing waters (Vannote et al. 1980). Clearing and certain other subsequent actions reduce or destroy the nutrient-providing function of riparian vegetation.

Many of these seven major functions are interrelated, all are performed primarily by vegetation, and all are decreased or eliminated when riparian vegetation is degraded or destroyed. It should be noted that within riparian areas, many of these functions are in fact provided by wetlands, which are themselves often protected with buffers. Wetlands provide a range of diverse and important ecological services (presented in Chapter 5) that also have human benefits. These services include flood storage and retention, groundwater recharge, water purification and recreational and aesthetic opportunities. However, their proximity to human activities or urban land-uses, in particular, have led to cumulative impacts that damage wetland hydrology and water quality (Azous and Horner 2000).

Further riparian functions important to salmonids include exchange of water between the ground and the water body (hyporheal flow, Stanford and Ward 1988); flux of gravel between stream beds and banks, and light patterning, which salmonids (Butler and Hawthorne 1968) and invertebrates (Myers and Resh 2000) use for concealment.

Effects of Land Development on Aquatic Habitats and Species

Land development (e.g., houses, landscaping, clearing, agricultural activity, roads, piers, gravel mining, bridge building, filling, bank armoring, bulk-heading) can significantly alter the natural watershed processes and habitat structures to which native plants and animals are adapted. Depending on the type of habitat affected, biological consequences may result from changes in the quantity and quality of spawning, rearing, migration, and refuge habitats, availability and quality of food, greater exposure to predators and increased competitive interactions. The effects of development varies by where it occurs in relation to the aquatic area. Three locations are discussed below:

(1) ***at the edge of, on top of, or within*** an aquatic area;

(2) ***in floodplains and riparian corridors***; and

(3) ***watershed-wide.***

At the edge of, on top of, or within

Development that occurs *at the edge of, on top of, or within,* an aquatic area can affect the quantity and quality of aquatic habitats by directly eliminating a habitat or altering natural processes that support it, such as bank erosion, channel migration, and the delivery and transport of sediment and woody debris. County-wide, in rivers and streams, four ubiquitous and significant activities impacting habitat quality and or quantity have been:

- The direct removal of LWD for salvage, navigation, recreation, fuel and/or aesthetics (Maser et al. 1988; Booth et al 2003; Collins et al. 2003)
- Streambank armoring for flood and erosion protection on all waterbodies including marine, and river training or reclamation through diking (Beamer and Henderson 1998; Schmetterling et al. 2001; Collins et al. 2002)
- Construction of water crossing structures (May et al. 1997; Alberti et al. 2005)
- Placement of other barriers to fish passage such as dams, ponds, tide gates, and dikes that block access to productive habitats (Beechie et al. 1994)

In the Pacific Northwest, LWD is a key structural element important to salmonid habitat (Bisson et al. 1987; Maser et al. 1988; Stouder et al. 1997). Human activities, such as forestry, agriculture and road building have directly impacted LWD size, abundance, complexity of debris jams, and instream habitat conditions, indirectly affecting juvenile salmonid abundance and diversity (Bisson et al, 1987; Maser et al. 1988; Spence et al. 1996; Stouder et al. 1997). When LWD is removed, stream channel form shifts from alternating pool:riffle sequences to a plane-bed form (Montgomery and Buffington 1997), which has been correlated with a reduction in stream spawning capacity and use (Montgomery et al. 1999). There is also a reduction in pool habitat for rearing in terms of quantity and quality. For example, coho salmon have a strong preference for low-flow habitats (pools, off-channel ponds, sloughs) with complex cover and debris (Bisson et al. 1982; Tschaplinski and Hartman 1983; Swales and Levings 1989).

Urbanization has had similar impacts, but effects may be more permanent, especially when coupled with hydrologic impacts from an altered watershed and from floodplain and riparian degradation (May et al. 1997; Booth et al. 2002). To date a significant amount of research has contributed to an understanding of how impacts related to urbanization affect aquatic areas and their constituent elements; notably, channel morphology, LWD, pool habitat for salmonids, streambank and streambed stability, and fine sediment composition or embeddedness of spawning gravels (May et al. 1997, Booth et al. 2002). Importantly, these conditions *at the edge of, on top of, or within* an aquatic area (e.g.; the Physical Stream Conditions Index, McBride 2001; the Qualitative Habitat Index, May et al. 1997), have been strongly correlated with measures of ecological health, such as the B-IBI (May et al. 1997; McBride 2001).

The effects of bank armoring on riverine, estuarine, and marine shoreline habitats, species and watershed processes are well documented and understood both in terms of direct and indirect effects. Direct effects include the alteration of substrate within or at the edge of water, which changes the surface condition and or type (Haas et al. 2003) and the elimination of undercut or overhead bank cover (Schmetterling et al. 2001). This has been shown to alter the suitability of habitats for salmonids in rivers (Beamer and Henderson 1998). Beamer and Henderson (1998) showed a decrease in use of riprapped banks in the Skagit River compared to natural banks. Additionally, on armored banks the growth of natural vegetation is limited and the recruitment of large woody debris from streambanks is restricted (Schmetterling et al. 2001). In rivers, armoring acts to prevent channel migration and isolates floodplain processes and habitats from the main channel. In the absence of lateral channel adjustment, channel adjustment can be downward, which increases gradient, undermines streambanks, and further alters rearing and spawning habitats for salmonids and other biota. In marine areas, shoreline armoring acts to completely cover habitats or alter substrates through hydraulic changes. Often finer sands and gravels are scoured and larger cobble and boulders predominate (Williams et al. 2001). Landward of shoreline armoring, natural recruitment of sand, soils and gravel to the nearshore from bluffs becomes interrupted by armoring (Williams et al. 2001).

In Snohomish County, prevalent and important activities affecting stream-riparian ecosystems are:

- Agricultural activities such as farming and livestock grazing (Murphy and Meehan 1991),
- Gravel scalping (Kondolf et al. 2002),
- Vegetation maintenance on armored banks, and
- Stormwater discharge (e.g., Booth and Reinelt 1993).

Improper grazing practices can degrade stream and riparian areas from the loss of riparian vegetation due to direct grazing and trampling, erosion of streambanks due to livestock access, and increased turbidity from fine sediment inputs. In general, research has indicated that use of proper agricultural Best Management Practices (BMPs) such as limiting livestock access to the stream and riparian area using fencing and maintenance of vegetative buffers along the riparian corridor can significantly reduce the impacts of agricultural activities (Lowrance et al. 1984).

Additionally, Canning and Shipman (1995), Chrzastowoski (1983), and Haas and Collins (2001) document dramatic changes in marine and freshwater habitat as a result of human development occurring *within, on top, or at the edge of* aquatic areas. Williams et al. (2001) provide an extensive discussion of the effects of shoreline modification on marine and estuarine habitats and species. Similarly, Nightingale and Simenstad (2001) provide an extensive review of effects of overwater structures (e.g., docks and piers). Effects of such activities and structures include changes in currents, amount and transport rates of shoreline sediment and woody debris, changes in night-time ambient light levels (developed areas are often much brighter at night due to lighting), introductions of toxic chemicals, and reductions in the quantity and quality of habitat.

In Floodplains and Riparian Corridors

Development *in floodplains and riparian corridors* affects aquatic areas when it removes or modifies native forest vegetation, or when it alters rates and patterns of bank and channel erosion, migration, surface, and groundwater flow. Riparian areas provide a variety of functions including shade, temperature control, water purification, woody debris recruitment, sediment delivery, terrestrial-based food supply, and channel, bank, and beach erosion (Gregory et al. 1991; Naiman and Bilby 1998; Spence et al. 1996). These are potentially affected when riparian and floodplain development occurs (Waters 1995; Stewart et al. 2001; Lee et al. 2001). Bolton and Shellberg (2001) provide an extensive discussion of the effects of riparian and floodplain development on aquatic habitats and species. Effects include:

- A reduction in amount, complexity, and connectivity of habitat within floodplain and riparian corridors from clearing, utilities, and increasing road crossings (May et al. 1997; Alberti et al. 2005);
- Increased scouring of channels due to channel and floodplain confinement (May et al. 1997) that further isolates the river from its floodplain;
- A reduction or loss of channel migration, natural vegetation (an increase in invasive species), sediment supply; and
- A reduction or loss of woody debris recruitment (Maser et al. 1988; Bilby and Ward, 1991).

Human activities in riparian and floodplain areas can have adverse impacts on LWD abundance, distribution, and function (Maser et al. 1988; Bilby and Ward 1991). Even if LWD is not directly removed from streams in conjunction with forestry, agricultural, transportation or urbanization activities, for example, the quantity and quality of LWD diminishes over time because impacted or urbanized riparian zones can not provide LWD at normative levels (Maser et al. 1988; May et al. 1997). Recovery of LWD recruitment potential to natural levels can take many decades (Maser et al. 1988; Bisson et al. 1987; Bilby and Ward 1989).

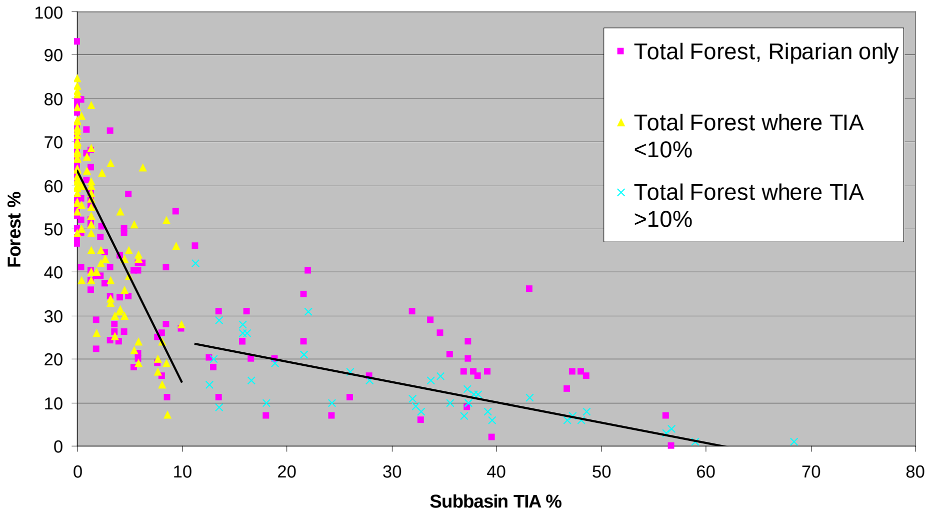
The fragmentation of riparian corridor continuity also impacts the functional quality of riparian and floodplain areas and has direct consequences for the quality and quantity of aquatic habitats (May et al. 1997). Road and utility crossings, land clearing, filling and encroachment from urban development in floodplain and riparian corridors effectively reduce buffer functions, alter hydrologic pathways, often directly discharge pollutants from drainage networks and fragment high quality patches of habitat (May et al. 1997; Alberti et al. 2005). Importantly, these conditions *in floodplains and riparian corridors* have been strongly correlated with measures of ecological health, such as the B-IBI (Morley and Karr 2002; Alberti et al. 2005). Taken together, riparian corridor width, connectivity, riparian forest maturity, natural forest and wetland land cover, floodplain interactions, and vegetation type have been used to describe riparian integrity for streams in the Puget Sound region (Horner et al. 2002). Based on this approach, an index of riparian integrity has been developed to characterize existing conditions based on impacts from land development, identify targets for restoration, establish a monitoring context for riparian and floodplain areas, and use in modeling efforts so that the variability in indicators of ecological health (such as the B-IBI) can be evaluated based on riparian and floodplain conditions and functions. An extension of this approach is to evaluate how development that *occurs watershed-wide* (as landscape impacts) may affect aquatic areas.

Watershed-wide

Development that *occurs watershed-wide* may have the potential to affect aquatic habitat primarily when it modifies water storage and runoff patterns and sediment erosion and delivery rates (Harr et al. 1975; Hicks et al. 1991; Booth 1990; Booth and Reinelt 1993; Booth and

Jackson 1997; Booth and Henshaw 2001; Booth et al. 2002). Booth and Reinelt (1993) found that when a watershed reaches approximately 10 percent effective impervious area, that demonstrable, and probably irreversible, loss of aquatic system function occurs in western Washington streams. They and May et al. (1997) also noted that detrimental effects on channel conditions or habitat quality were evident well before 10 percent was reached and that no "threshold of effect" was observed. However, this likely has as much to do with a dramatic decrease in forested land cover at the watershed scale and within riparian corridors as it does with the increase in impervious area up to 10 percent (shown in Figure 3.3 from Snohomish County data by Purser et al. (2002)). In fact, in Snohomish County the relationship between impervious area and forest cover is strikingly discontinuous up to and above approximately 10 percent impervious area. Models developed to explain the variability in aquatic habitat conditions or biological response (e.g., B-IBI) should incorporate both forest cover and impervious area as well as other factors. For example, in 42 subbasins in Snohomish and King Counties, Alberti et al. (2005) reported significant positive correlations between instream biotic integrity and the location and spatial configuration of forest cover, road density and crossings, and the locations and densities of different types of development. Their results suggest biological integrity is well correlated with land cover condition (both %Trees and %TIA) within 100m of a stream. The strongest correlation observed (r^2=0.68) was between biological integrity and stream road crossing frequency.

Figure 3.3. The relationship between subbasin total impervious area (TIA) and subbasin and riparian total forested land covers in Snohomish County.



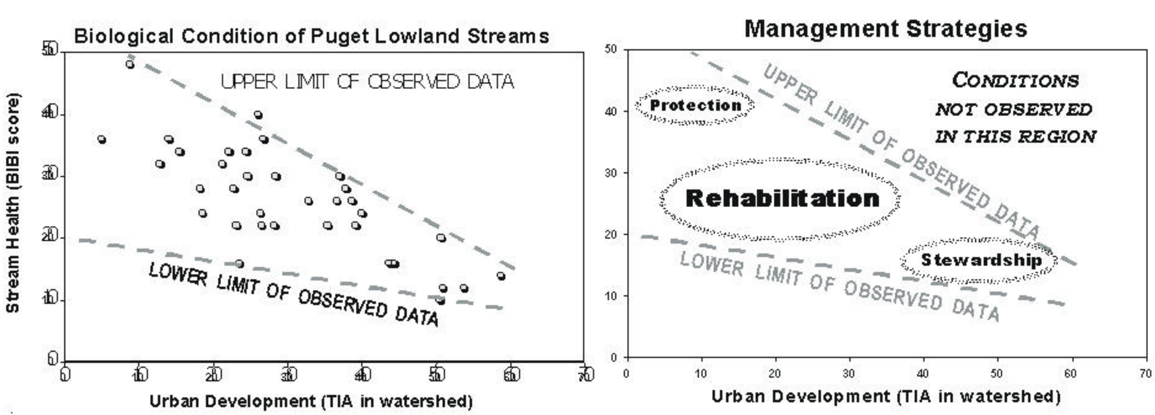
Horner et al. (2002) offer a more detailed approach to watershed analysis for urbanizing areas of Puget Sound that includes factors shown to *impact* biotic integrity or habitat conditions (such as impervious area or riparian encroachment or road crossing frequency) and factors that have *mitigative* value (such as forest and wetland area and riparian extent and quality). Research by these authors and others (May et al. 1997; Booth et al. 2004) have shown that at low levels of watershed development (i.e. <10 % impervious area) the observed high variability in biotic integrity or habitat conditions is governed by strong sensitivity to forest cover reduction (Figure 3.4, left panel from Booth et al. 2004). At the very highest levels of development, the observed variability in biotic integrity is low as are the measures of biotic integrity or habitat conditions presumably because impacts associated with land development, hydrologic alteration, and riparian degradation overwhelm remaining mitigative factors. In these areas successful restoration of natural conditions is unlikely, thus management approaches based on doing no further harm (especially through critical areas regulation and treatment of stormwater quantity and quality) and stewardship activities are beneficial (Figure 3.4, right panel; Booth et al. 2004).

Mitigative Measures

Where land development is intermediate, there appears to be high variability in both habitat conditions in aquatic areas (May et al. 1997) and measures of biotic integrity even given usually lower levels of remaining forest cover and alteration of hydrologic regime (Booth et al. 2004). In numerous studies, it has been demonstrated that the mitigative value of higher quality or intact riparian and floodplain corridors contributes substantially to the retention and even improvement of biotic integrity and habitat conditions (May et al. 1997; Morley and Karr 2002; Booth et al. 2004). For example, this has been documented in Snohomish County in Little Bear Creek (Morley and Karr 2002). In addition, Booth et al. (2004) demonstrated that biotic integrity as measured by B-IBI, was higher in subbasins where riparian areas had less urban land cover. Hence it is in these areas where rehabilitation is likely to succeed (see Figure 3.4), dependent upon the correct identification of factors affecting aquatic areas and treatment of causes as well as effects.

Other management strategies that have proven to have a mitigative effect on water quality and quantity include adopting improved stormwater management plans, equivalent to Department of Ecology's 2001 Stormwater Manual.

Figure 3.4. Biological Integrity, Watershed Condition, and Management Strategies From Booth et al. 2004. Left panel depicts limits of observed data and range of biological integrity among subbasins relative to existing watershed condition in the Puget Sound lowland region. Right panel depicts a management strategy based on observed conditions.



Wherever it occurs, development has the potential to affect species migration and dispersal patterns by isolating habitats and fragmenting the landscape (McKinney 2002). It also tends to expose plants and animals to unnatural and potentially very harmful chemicals (Scholz et al. 2000), and puts people and their pets in close proximity to native plants and animals that may not be tolerant of them (Baker and Haemmerle 1990). Finally, there are many ways in which these changes affect plants and animals. In general, the physical and chemical effects are to create hydrologically simplified and/or polluted aquatic habitats with disturbance regimes much different from pre-development conditions (e.g., dramatically more or less intensity or frequency of flooding, erosion, or fire). In turn, native species diversity, distribution, abundance and productivity is lost or greatly reduced, especially among the most pollution intolerant species. Oftentimes these changes contribute to, or their effects are exacerbated by, invasions of undesirable, pollution-tolerant invasive or exotic species (May et al. 1997; Harding et al. 1998; Frissell 1991; McKinney 2002; Waters 1995; Stewart et al. 2001).

Processes Conclusion

Aquatic areas and the native species that use them have evolved in response to processes that reflect the ongoing interactions of water, soil, vegetation communities and animals at local, regional and global scales over long temporal scales (hundreds to millions of years). Without providing substantial habitat protection, development may cause reductions (sometimes very dramatic) in productivity and species diversity, and contribute to damage caused by invasive, pollution tolerant and exotic species, which commonly benefit from habitat degradation.

While salmonids are often used as benchmark species, their use as an ecological indicator species is complicated by the influence of harvest, hatcheries, and ocean conditions. Other species, such as amphibians, molluscs, and insects may be better indicators, depending on the effect and habitat being assessed.

Stormwater Management and Aquatic Areas

(*See Appendix A for additional discussion on Stormwater Mitigation Measures*)

The changes in landscape that occur with increased human population typically results in changes in the hydrologic regime, including evapotranspiration, surface flow patterns, and groundwater flow patterns. This section provides an overview of the impacts of these changes.

As will be referenced in detail below, numerous studies have shown that development within a watershed can be directly linked to physical degradation of aquatic areas and, in turn, the quality of habitat they provide.

The initial hydrologic 'during-a-storm' consequences of development are increased volume and flow rate of stormwater. These effects in turn result in a decreased time of stormwater delivery to a receiving water, increased frequency and duration of high stream flows, and greater streamflow velocities. The flow effects in streams in turn result in increased sediment mobility, stream channel instability (for some period at least), and alteration of the 'stable' channel form. Finally, these effects can cause harm to the biota of the streams. Similar effects are seen in wetlands.

The changes in hydrology during storms result in corresponding changes between storms. Under predevelopment conditions, much of the rainfall is either captured and released by evapotranspiration via the forest canopy, or it infiltrates into the soil, and does not reach surface water for days, weeks, or months. Since development causes more water to run off the land surface, less of it infiltrates into the soil, which may affect baseflows at all times of year, particularly in the dry summer months.

In addition to hydrologic impacts, stormwater generated by land development contains elevated concentrations of pollutants, most of which are not present in the environment in detectable quantities absent introduction by humans.

Stormwater Flow Impacts

Booth (1990) cites Hollis (1975) as having synthesized many separate studies to show that the dual factors of percent impervious area and percent of a watershed served by storm sewers increase the peak discharges of floods. Specifically, at total impervious percentages of 10% - 20% (low-density suburban development), peak flow increases of up to two-fold to three-fold typically occur for flows with recurrence intervals between one and ten years. Booth and Jackson (1997) cite Barker et al. (1991) as stating that, in urbanized areas, the flow duration of any given flow magnitude increases by factors of five to ten. For additional reference, Dinacola (1989) states that a residential area of 1 dwelling unit per acre has about 20% total impervious area (TIA), and an area with 4 dwelling units per acre has about 35% TIA. The latter density is typical for urban residential areas with single family detached dwellings.

These alterations in hydrology can result in significant changes in stream channel geomorphology. While some streams may approach a new equilibrium state in which the overall form of the stream and the basin are simply larger cases of the predeveloped conditions through a relatively slow expansion of the channel width and depth, other stream channels may exhibit catastrophic stream incision (Booth 1990). Land cover changes also increase the annual sediment mass delivered to the streams, which can significantly shift the sediment size distribution in gravel-bed streams toward a predominance of finer sediments (Booth and Jackson 1997).

A seminal publication by Booth and Jackson (1997) developed correlations between the extent of urbanization and stream channel stability in 271 subcatchments of five major watersheds in King County, WA. They distinguished between stable and unstable channels on the definition set forth by Galli (1996), in which stable channels have little or no erosion of their beds and banks, while unstable channels have long and continuous reaches with bare, destabilized banks indicative of significant channel widening and incision. Booth and Jackson collected stream channel stability data and flow data, and used the Hydrologic Simulation Program – Fortran (HSPF) model to simulate discharges in the five study watersheds using long-term rainfall records and various land cover inputs. Their analysis of the observed channel conditions, the percent Effective Impervious Area (EIA) in the subcatchment, and the ratio of the modeled 10-year forested peak flow to the measured 2-year existing-condition peak flow showed two strong correlations. First, an EIA of above 10% correlates with unstable channels "almost perfectly." Second, unstable channels correlate very strongly with watersheds in which the 10-year peak flow under forested conditions has a 2-year recurrence interval under existing conditions.

Recently, several researchers have examined the extent to which streams in urban areas equilibrate to a new stable channel configuration, and have questioned whether the apparently stable channels and riparian zones provide adequate conditions for the biota traditionally found in the streams. Finkenbine et al. (2000) studied rural and urbanized streams in the vicinity of Vancouver, B.C. Their measurements found that the stream beds actually had a lower percentage of fine sediment than was the case before urbanization, and that intragravel dissolved oxygen in the urban streams was higher than in the rural streams, although they also found summer baseflows were reduced in watersheds with total impervious area (TIA) greater than 40%, and a watershed with TIA > 20% had a scarcity of large woody debris. Based on the sediment size fraction data, they asserted that the urban stream channels had reached a new geomorphic equilibrium in the 20 years after watershed urbanization, and stated that "it appears that spawning conditions have not been degraded by the change in flow regime. The larger material transported in the urban streams is beneficial, as it provides cover to fish and contributes roughness which slows flows." They also stated that adequate riparian vegetation and large woody debris were critical factors in urban stream equilibration.

Hartley et al. (2001) sharply countered the conclusions of Finkenbine et al. (2000), stating that while the urban streams studied had larger sediment and more dissolved oxygen, any benefits to fish would be outweighed by the observed reduction in summer low flows, the probability of increased temperature due to lack of shade in wider channels, more frequent channel disturbances with high flows, greater potential for scouring of redds and eggs, impaired water quality in urban streams, and impaired macroinvertebrate communities in urban streams. They stated that "a decades-long waiting period following urbanization does not return a stream to the same hydraulics and functional habitat or a wider scale model thereof. Rather, significant urbanization causes a shift from a natural geomorphologic disturbance regime to a radically altered one with not only increased magnitude, frequency, and duration of peak flows and velocities, but also increased flow oscillations, and exotic flow events such as out-of-season stream rises. These are altered states to which most predevelopment native aquatic biota are not like to be adapted." Finkenbine et al. (2001) acknowledged these criticisms as valid.

Henshaw and Booth (2001) studied restabilization of urban stream channels in the Puget Sound area. They reached the following conclusions:

- restabilization of urban streams occurs in the study area;
- the degree of stability is not well predicted by the magnitude of developed area or the rate of recent development;
- most streams in the study area will probably equilibrate within 10 to 20 years of cessation of land cover alteration; and
- the primary factors in restabilization are the hydrologic and geomorphic characteristics of the channel and the watershed, not the magnitude or rate of development.

The degree to which urbanization causes low stream flows by reducing rainfall infiltration has been examined as well. Burges et al. (1998) estimated the hydrologic balance using a hydrologic model and field monitoring for two geographically close zero-order watersheds in the Puget Sound lowlands of King County, WA. Four years (1990-1993) of data were presented. The hydrologic model was similar to one reported on by Wigmosta and Burges (1990). One watershed was covered in mature second-growth forest, and the other contains a suburban development with approximately 30% effective impervious area and reduced soil thickness and quality. Surface runoff in the forested watershed was estimated as 12% and 30% of the total rainfall volume, while in the developed watershed surface runoff was between 44% and 48% of the rainfall. A component of this difference was the typically lower (modeled) infiltration in the suburban watershed, caused by the reduced soil column in that watershed.

Konrad (2000) studied 59 Puget Sound lowland streams. He found that in the late spring and summer, the discharge rate of urban streams declined to a steady level by May 31, whereas base flow from less urban basins continued to decline throughout the summer. Konrad also documented the spatial extent of low-flow conditions in August 1998 and 1999, and found that drainage area alone did not reliably discriminate ephemeral streams from perennial streams. Streams draining 1.2 km^2 had a 50% probability of being dry during summer base flow conditions, or 'ephemeral,' but there was considerable variability around this value: streams with drainage areas less than 0.1 km^2 had a 5% probability of perennial flow, and streams with drainage areas greater than 5 km^2 had a 95% probability of perennial flow. Further, road density (length of roads in a basin divided by the basin area) as an index of urbanization did not correlate strongly with ephemerality or perenniality of streams. Surficial geology was a more reliable indicator, in that the transition between perennial and ephemeral streams was typically found near the contact between advance outwash or recessional outwash deposits and glacial till (Konrad 2000).

McBride and Booth (2005) assessed physical conditions in urban streams in the Puget Sound Lowland region according to the Physical Streams Conditions Index (PSCI) and examined correlations with landscape metrics determined through a geographic information systems (GIS) analysis. The study evaluated a total of 70 sites in four watersheds: Juanita creek, Swamp Creek, Little Bear Creek, and Thorndyke Creek. Stream conditions as measured by the PSCI improved when a stream flowed through an intact riparian buffer with forested or wetland vegetation and without road crossings.

Evapotranspiration (ET) from urbanized landscapes in the Puget Sound region, especially during the winter months, is not documented by field measurements. The literature on evaporation and ET in the winter in the Puget Sound from shrubs and grasses is sparse. Much of the general ET literature has focused on either mature forests, or on agricultural situations of high ET and limited water, which is the opposite hydrological context from the critical setting for stormwater management in Puget Sound. Burges et al. (1998) refer to Bosch and Hewlett (1982) and Ffolliott and Thorud (1977) as resources for general discussions on the influence of changes in vegetation on water yield and ET**.**

HSPF modeling by Beyerlein (1999) showed that for forested conditions in the Puget Sound area, about 45% of the annual rainfall is returned to the atmosphere by evapotranspiration. A study of the graphs presented by Burges et al. (1998) showed that in a suburban watershed in the Puget Sound lowlands, modeled wet-season (Oct. 1 – Apr. 30) ET returned about 25% to 50% of the wet-season precipitation to the atmosphere. However, examination of their data show that during the months of December through February, modeled ET tended to be about an order of magnitude lower than rainfall, which implies that during the months in which storms that drive detention pond sizing tend to occur, ET may not be a factor for which manipulation will significantly reduce runoff and thus detention pond sizing. More field data on this topic would be quite useful. Blight (2002) demonstrated through greenhouse experiments that more water can be lost via evaporation from bare saturated soil than from a water surface, but that as soil dries the evaporation rate falls below that from a water surface. He also showed that even a low velocity wind can significantly increase the evaporation rate. However, his results were at temperatures more typical of a Puget Sound area summer than winter.

Urbanization has been observed to have negative effects on riparian biological communities. Booth et al. (2002) credits Klein (1979) as the first such study, in which a rapid decline in biotic diversity in watersheds was correlated with a total impervious area greater than 10%. Numerous similar studies followed, including Steedman (1988), and a compilation of various studies by Schueler (1994). In addition to the search for the useful indices of landscape, hydrology, and stream geomorphology, and useful correlations among them, there has also been a search for biological indices. One of the most prominent biological indices that emerged in the 1990s is the Benthic Index of Biological Integrity, or B-IBI, discussed by Karr (1996). This index has been used extensively as a measure of general stream health. Booth et al. (2002) presented a graph that plotted percent total watershed imperviousness against B-IBI scores. The data were compiled from studies by Kleindl (1995), May (1996), and Morley (2000), and show a general decline in B-IBI with increased imperviousness, but also show that some watersheds had a significantly reduced B-IBI with less than 5% total impervious area.

Stormwater Pollution Impacts

Stormwater pollution impacts have been extensively documented (Bannerman et al. 1993; Charlesworth and Lees 1999; Davis et al. 2001; Minton 2002a; Morrison et al. 1984; Morrison et al. 1990; Pitt 1985; Pitt et al. 1999; Sansalone and Buchberger 1997; Sansalone et al. 1998; Sartor et al. 1972; and USEPA 1983.

Many pollutants adsorb to sediments in stormwater. Further, Sartor et al. (1972) and Pitt (1985) showed that a disproportionately large weight percentage of metals, pesticides, and nutrients are adsorbed onto silt-sized and clay-sized particles, although a significant fraction of the metals and pesticides adsorb to sand and larger particles. Pollutants also form complexes with humic substances, which can lead to removal to adsorption, coagulation, or precipitation. A detailed discussion of pollutant removal by these processes is found in Minton (2002a).

Approaches to Managing Aquatic Areas

Effective protection measures should provide protections for both critical habitats as well as ecological processes (water flow, sediment routing, vegetation succession, woody debris processing, and plant and animal speciation) that sustain them. Aquatic areas, the species that use them, and the ecological processes that sustain them occur at multiple habitat (aquatic, riparian and landscape) and time (days to centuries and longer) scales. Therefore protections should address potential impacts and protection needs at those multiple scales (Booth and Reinelt 1993). This means having regulations that protect aquatic habitats from direct harm from in-water and riparian activities as well as protecting key riparian and upland functions that sustain aquatic habitats.

In lieu of increased protection standards, many attempts have been made to mimic natural processes, such as through artificial stormwater or streambed controls, or hatcheries. Unfortunately, such approaches generally have been found to be ineffective or counter-productive and costly substitutes for natural conditions (see Booth and Jackson 1997; Booth et al. 2002; National Research Council 1996; Roper et al. 1998; Frissell and Nawa 1992). In some cases where larger landscape processes were not adequately considered, they have generated additional problems and costs rather than solutions (Kondolf 2000; Booth et al. 2002).

Some extensively urbanized parts of the landscape may be irreversibly impacted, particularly the hydrologic regimes (Booth and Reinelt 1993; Booth et al. 2002). In such situations, artificial, highly engineered measures such as stormwater ponds, piping systems, and retrofitting of stream channels with artificial bed controls may be the only realistic choices left. Where such thresholds have not been reached, however, planning for and accommodating natural rates of change is considered one of the keys to sustaining aquatic habitats and the species that use them. In order for this to happen, it is necessary to maintain or restore where impaired, the processes that allow water, soil, vegetation, and animals to interact.

Approaches to Managing Riparian Areas

The most common method for protecting vegetation and its riparian functions from adjacent land uses has been the use of buffers. Castelle and Johnson (1998) define buffers as vegetated zones located between natural resources, such as streams, wetlands, or critical wildlife habitat, and nearby areas subject to human alteration. In general, riparian buffers should be designed based on the functions and values of the resources to be protected and in proportion to the risk posed by the surrounding land-use or potential activities. Therefore, fixed riparian buffers are intended to protect an area of sufficient size to provide functions considered important for protecting aquatic and riparian species and to buffer against development impacts (Haberstock et al. 2000). Key functions considered in establishing the width of buffers include shade and temperature regulation, flood conveyance, water quality protection and pollutant removal, nutrient cycling, sediment transport, bank stabilization, woody debris recruitment, wildlife habitat and microclimate control (Spence et al. 1996; IMST 2002; May 2000).

A variety of technical reports summarize the scientific literature on buffer functions and make recommendations for buffer widths. Findings of three such reports are shown in Tables 3.1, 3.2, and 3.3; (from Parametrix 2002). Others include Castelle et al. (1992), Castelle and Johnson (2000), Desbonnet et al. (1994), Johnson and Ryba (1992), and Pollock and Kennard (1998).

Site Potential Tree Height (SPTH)

FEMAT (1993) defined a SPTH as the average maximum height to which a dominant old growth tree will grow if left undisturbed. Depending on the species, soils, climate, and disturbance history of a site, a dominant tree could be between 200 to 500 years old. Pollock and Kennard (1998) provide detailed explanation of a SPTH. Using tree growth information for two riparian plant association groups (PAGs) on the Mount Baker-Snoqualmie National Forest, they estimate the SPTH for Douglas Firs would range from 218 to 198 feet for PAGs four and five, respectively. Similar data are not readily available for other trees, such as western red cedar, sitka spruce, which can be as tall or taller than Douglas Firs, depending on site conditions, or for black cottonwood, red alder and bigleaf maple, which are smaller in maximum height and therefore would likely have smaller SPTH values than for Douglas fir. Soil surveys by the U.S. Department of Agriculture, Soil Conservation Service, typically provide estimates of tree height for given soils. However the information is based on growth achieved in fifty or 100-years and thus do not represent a site's SPTH for longer lived trees such as Douglas firs, western red cedars or sitka spruce. For example, for Alderwood soils, which are the dominant soils for Snohomish County, the average height of a 100-year Douglas fir would be 146 feet, roughly 75 to 80 percent of the SPTH assuming a 300-year-old tree (Pollock and Kennard 1998). The county-wide 100-year SPTH average is 150 feet (un-weighted by geographical area), with a range of 60-185 feet (Debose and Klungland 1983),. It should be noted that SPTH and the functions provided would be applicable to lakes, ponds, and other aquatic areas.

The concept of scaling riparian buffer widths to the potential height of a tree was first proposed by the Federal Ecosystem Management Team who was assessing riparian protections for national forest lands (FEMAT 1993). They reasoned that trees were a logical scaling factor because (1) they are a dominant factor in determining habitat conditions and (2) when left unmanaged, their size (height) reflected inherent productivity and constraints of a given site. As a result of this logic, generalized curves using scientific data and professional judgment were developed to help rate buffer effectiveness for a variety of ecological functions, including shade, litter fall (e.g., leaves, branches), root strength and woody debris inputs. Curves for a set of factors (soil moisture, radiation, soils temperature, air temperature, wind speed, and relative humidity) relating to microclimate were also developed. These curves are shown in Figure 3.5.

Based on these curves, all but microclimate functions would likely be protected with a buffer width equivalent to one SPTH. Microclimate functions would need approximately three SPTH for full protection.

Figure 3.5. Riparian vegetation effectiveness as a function of the height of a site potential tree distance from the water's edge.

Graph (a) shows cumulative effectiveness of four riparian processes as a function of relative distance from the edge of a stream, in fractions of a dominant tree height. Graph (b) shows cumulative effectiveness for six microclimate factors as a function of relative distance from the stream edge. Modified from FEMAT (1993) and Naiman et al (2000).

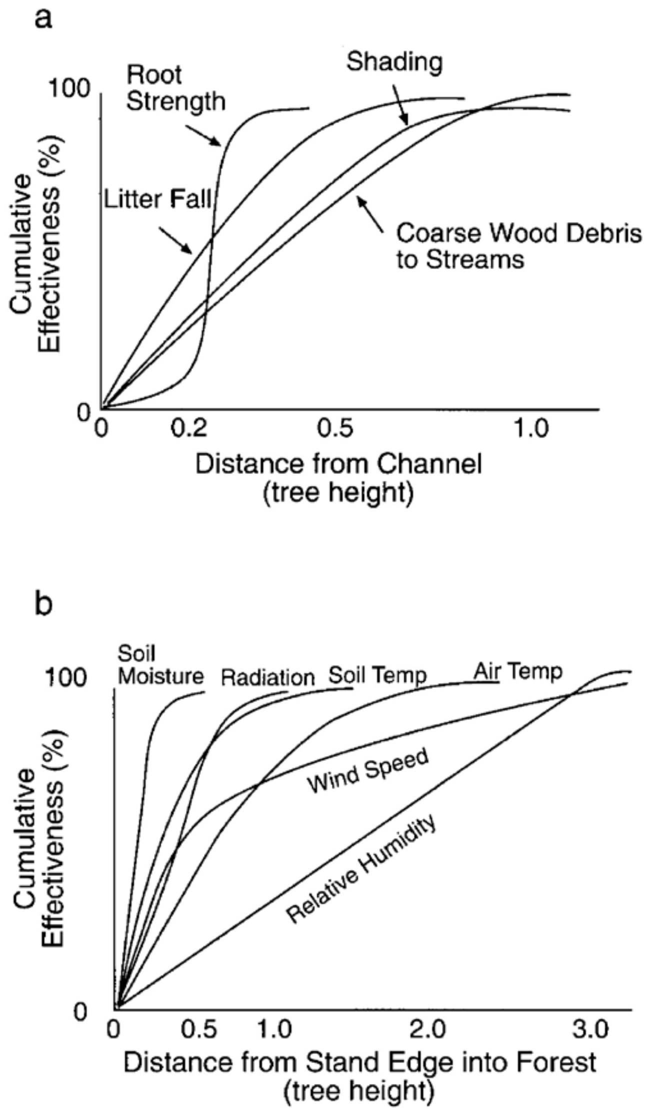


Table 3.2. Riparian Buffer Functions and Appropriate Widths Identified by May (2000).

Function	Range of Effective Buffer Widths	Minimum Recommended	Notes On Function
Sediment Removal/Erosion Control	26 - 600 ft (8 – 183 m)	98 ft (30 m)	For 80% sediment removal
Pollutant Removal	13 - 860 ft (4 - 262 m)	98 ft (30 m)	For 80% nutrient removal
Large Woody Debris Recruitment	33-328 ft (10 –100 m)	262 ft (80 m)	1 SPTH based on long-term natural levels
Water Temperature Protection	36 - 141 ft (11 – 43 m)	98 ft (30 m)	Based on adequate shade
Wildlife Habitat	33 - 656 ft (10 – 200 m)	328 ft (100 m)	Coverage not inclusive
Microclimate Protection	148 - 656 ft (45 – 200 m)	328 ft (100 m)	Optimum long-term support

Table 3.3. Riparian Functions and Appropriate Widths from Literature Identified by Knutson and Naef (1997).

Function	Range of Effective Buffer Widths
Water Temperature Protection	35 - 151 ft (11 - 46 m)
Pollutant Removal	13 - 600 ft (4 - 183 m)
Large Woody Debris Recruitment	100 - 180 ft (30 - 61 m)
Erosion Control	100 - 125 ft (30 - 38 m)
Wildlife Habitat	25 - 984 ft (8 - 300 m)
Sediment filtration	26 - 300 ft (8 - 91 m)
Microclimate	200 - 525 ft (61 - 160 m)

Table 3.4. Riparian Functions and Appropriate Widths Identified from FEMAT (1993).

Function	Number of SPTH	Equivalent Based on SPTH of 200 ft (m)
Shade	0.75	150 ft (46 m)
Microclimate	up to 3	up to 600 ft (183 m)
Large Woody Debris	1.0	200 ft (61 m)
Organic Litter	0.5	100 ft (30 m)
Sediment Control	1.0	200 ft (61 m)
Bank Stabilization	0.5	100 ft (30 m)
Wildlife Habitat	-----	98 - 600 ft (30 - 183 m)

Fixed Versus Variable Width Buffers

Approaches to establishing buffers vary between fixed or variable width, with the former generally being the most common (Haberstock et al. 2000). Castelle and Johnson (1998) note that fixed buffer widths are more easily established, have a lower need for specialized personnel with knowledge of ecological principles, and require less time and money to administer. Conversely, they note that variable width buffers can potentially allow for greater flexibility, account for variation in site conditions (provided these can be measured and well documented) and land management practices, and potentially achieve desired ecological goals while minimizing loss of useable land area to landowners. Variable width buffers are considered ecologically feasible because they have the potential to reflect the true sensitivity of the environment and management goals (Haberstock et al. 2000; IMST 2002). Castelle et al. (1992) indicate that the more sensitive or critical the area to be protected is, the wider the buffer needed to protect it. To ensure success in the face of uncertainty about specific site conditions, May (2000) and Haberstock et al. (2000) suggest that fixed-width buffers should be designed conservatively (i.e., larger than the bare minimum needed for protection).

Variable width buffer approaches have been proposed by Forman (1995) and, as cited by Castelle and Johnson (1998) by Steinblums et al. (1984), Budd et al. (1987), and Groffman et al. (1990). Haberstock et al. (2000) provides recommendations for a variable width two-zone approach for the protection of endangered Atlantic salmon habitat. In their approach, Zone One is a fixed 35-ft (10.7-m) width closest to the water in which no disturbance should occur. Zone Two is a variable-width area wherein limited low-impact uses (recreation, low-impact forestry) that do not compromise the desired functions of the buffer could be allowed. Total buffer widths (Zone One plus Zone Two) range from a minimum of 70 feet (21 m) to 400 feet (122 m), with a maximum of 1,000 feet (305 m) in rare cases, such as along streams that are flanked by extensive steep (> 25 percent) slopes.

Adjustments in Zone Two width can be made for the presence of surface and groundwater seepage features, forest floor roughness, sand and gravel aquifers, wetlands, floodplains, very steep slopes, and stream order. All but one of the adjustment factors (the degree of forest floor surface roughness) causes Zone Two to increase. These authors note that buffer widths are expected to vary regionally as a function of buffer conditions, management objectives, and instream habitat characteristics. They also note that this is a conceptual model and potentially subject to change as studies and scientific literature provide new data that better indicate the relationships between buffer characteristics and buffer effectiveness.

There is no consensus in the scientific literature regarding single buffer widths for particular functions, or to accommodate all functions. However, neither does the literature indicate that buffers are not needed, nor that riparian buffers beyond the equivalent of several site potential tree heights (SPTHs) are needed. One SPTH, the maximum height a tree will attain given the existing geology, soils, and other site conditions, ranges from 50 to 250 feet (15-76 m), depending on species, for a tree at least 300 years old in western Washington forests. A buffer width equal to one SPTH would provide for a broad range of riparian functions important for sustaining salmonids. However, some wildlife, such as stream breeding amphibians, beavers and other mammals, may need considerably more than this for land migrations associated with foraging and breeding (see Table 3.7). Knutson and Naef (1997) recommend buffer widths ranging from 150-250 feet on streams and rivers, acknowledging their buffer recommendations “also provide additional riparian habitat area to meet the needs of specific wildlife species that occur in particular areas.”

The type and intensity of human activities in and near buffers are factors not often assessed in reviews of buffer widths, but they can affect conditions in the buffer. For example, in King County, in a survey of 62 Native Growth Protection Easements along streams, wetlands, and steep slopes in developing areas of western King County, Baker and Haemmerle (1990) found that the vegetated condition of two-thirds of the designated and protected buffer easements had been altered by people, and of those, 25 percent had been judged as being negatively affected. Moreover, the number and seriousness of impacts increased with increasingly intense residential development near the Easements. May (2000) suggests that more protective buffers are needed for more sensitive or valuable resources. Similarly, he suggests that more protective buffers should be applied for higher intensity land uses or when the land use poses higher risk of impact. This is, of course, dependent upon the establishment of management goals and objectives for buffer functions and not just the establishment of buffer widths for GMA compliance.

Marine Near-Shore, Estuarine, Lake and Pond Habitats

In many ways the functions of marine nearshore habitats are similar to those of streams and rivers and thus the buffer widths recommended for riverine habitats are also applicable to marine nearshore habitats. For example, as with streams, riparian areas can contribute significant amounts of food for marine fish. Duffy (2003) found that terrestrial invertebrates made up a large contribution of the diet of fishes in north Puget Sound. A study of marine fishes along King and Snohomish County shorelines also found terrestrial insects were a significant part of the diet of juvenile salmon (Brennan et al. 2004). Also, marine shorelines can be viewed as similar to riverine shorelines because of energy from tides, waves and currents; their condition is influenced by energy that scours, transports and deposits sediment and woody debris. Woody debris in marine nearshore environments is derived both from onsite vegetation and transported from offsite locations subject to longshore currents. Marine nearshore woody debris also contributes nutrients to nearshore environment, and is a major component in forming and maintaining shoreline structural habitat (Everett and Ruiz 1993).

With respect to the value of buffers for temperature and shading in the marine nearshore environment, Levings and Jamieson (2001) note that the temperature of surficial and interstitial water emanating from marine riparian areas and flowing into marine nearshore habitats may be affected by shading. Pentilla (2001) found that reduced survival of surf smelt eggs was related to reduced shade from trees overhanging marine nearshore spawning habitats. Freshwater aquifers emanating from underneath a riparian forest can discharge into the intertidal zone, creating localized fresh and brackish water habitats. Levings and Jamieson (2001) suggest that populations of some species of prey for marine fish (e.g., the amphipod *Paramoera bousfieldi*, Staude 1984) may be adapted to cool freshwater seeps as well as brackish conditions. The integrity of such aquifers and seeps could be affected by the integrity of the riparian vegetation (Levings and Jamieson 2001).

Levings and Jamieson (2001) also conducted a review of the literature pertaining to buffer width recommendations for protection of marine riparian habitat in British Columbia, Washington, and Alaska. Depending on shore class, recommended marine buffers zones in British Columbia range from approximately 300 feet (100 m) for Class B marine shores to approximately 450 feet (150 m) for Class A (1) and A (2) shores (those with low banks adjacent to open waters) (Ministry of Forests 1996; Levings and Jamieson 2001). In Chesapeake Bay, forest buffers of 35 to 125 feet (11 - 38 m) are recommended, depending on pollutant loading and site conditions (Palone and Todd 1977, as cited in Levings and Jamieson 2001). In addition, in the Tongass

National Forest, protection is recommended for a 1,000-foot-wide (305 m) beach fringe of mostly unmodified forest, primarily for wildlife habitat protection (Levings and Jamieson 2001).

Buffers for lakes and ponds are commonly prescribed, especially for protection of water quality. The basis for these prescriptions, however, seems to be derived from the literature for streams, rivers and wetlands, given the absence of scientific literature assessing functions or effectiveness of buffer widths for lakes and ponds. In a review of habitats and lakes, Schindler and Scheuerell (2002) note that studies of linkages between lakes and their riparian habitats are rare. Gasith and Hasler (1976) found that depending on riparian characteristics, shoreline complexity, and overall productivity of the aquatic system, litterfall from riparian vegetation can be a major source of organic matter to benthic and pelagic lake habitats (Schindler and Scheuerell 2002). In some instances, terrestrial insects can provide substantial inputs of prey for lake dwelling predators and contribute to lake nutrient cycles (Schindler and Scheuerell 2002). Schindler and Scheuerell (2002) also note that there has been almost no research on the roles of coarse woody debris (CWD) as habitat in lake ecosystems. However, they note that based on decomposition rates and habitat complexity associated with macrophytes, CWD would be expected to play a major role in providing habitat structure that could regulate predator-prey interactions along shorelines and in deeper benthic areas. For example, Tabor et al. (2004) observed that over 80% of all juvenile Chinook salmon at two sites surveyed from March-June were associated with small woody debris and overhanging vegetation.

While woody debris is an important component of lake and pond habitat structure and serves as a nutrient source, it may be that it has less of a hydraulic function since erosive energy gradients along lake and pond shorelines are lower than those along riverine and marine shorelines. Temperature regulation by riparian vegetation is probably less critical for lakes and ponds since the overall thermal condition of lakes and ponds is regulated more by air temperature and temperature of tributary inputs than by microclimatic controls provided by surrounding riparian forests. However, spring seeps and surface runoff into lakes and ponds can create localized temperature gradients, and their temperature regimes could be influenced by riparian conditions. Also, the temperature of small spring-fed ponds and littoral lake habitats with northerly aspects may be influenced by the condition (height, width, species composition) of adjacent riparian forests. Other functions, such as terrestrial food sources, overhead shade (for hiding cover rather than temperature), bank stability, and pollutant removal are likely similar for lakes and ponds as those affecting riverine and marine aquatic areas.

The riparian areas of estuaries are subject to tidal fluxes and their erosive energy is somewhat higher than for lakes and ponds and less than for streams, rivers, and marine shorelines, thus the science indicates that the hydraulic function of woody debris in estuaries would likely also be rather modest. However, estuaries often have areas of intense mixing either as a result of geomorphic constraints that focus tidal flow exchanges or due to extreme tidal fluxes during storms (Simenstad et al. 2000). Under such conditions, woody debris would play a similar hydraulic role as it does in more dynamic aquatic areas. Also, as with other habitats, woody debris plays a major role in providing estuarine habitat structure and contributes nutrients to estuarine ecosystems. Temperature regulation contributed by riparian vegetation on estuarine shorelines is probably less important than for streams and rivers, because overall estuarine temperatures are influenced primarily by marine and riverine inflows, depending on the type of estuary. However, as with the other aquatic areas, estuaries are likely to have seeps and other localized cool areas that may be affected by the extent and type of riparian habitat. Other functions, such as terrestrial food supply, overhead shade (for hiding cover rather than temperature moderation), bank stability, and pollutant removal (Williams et al. 2001) are similar to those affecting other aquatic areas.

Protecting Landscape Scale Functions

The best available science indicates that landscape scale measures (such as protection of forest cover and mitigation of stormwater) are needed to protect functions such as hydrology, sediment routing and nutrient cycling that largely originate outside of the immediate riparian corridor (May 2000; Haberstock et al. 2000). Physical (severe erosion and flooding) and biological (loss of species productivity and diversity) effects tend to be more pronounced in heavily urbanized areas with considerable impervious surfaces that disrupt natural streamflow (Booth and Reinelt 1993; Booth and Jackson 1997; May et al. 1997; Booth and Henshaw 2001). Streamflow quantity and timing affect water supply, water quality, and the ecological integrity of streams and is strongly correlated with water temperature, channel morphology, and habitat conditions (Dunne and Leopold 1977; Naiman et al. 2000). Given this, flow regulation should be regarded as much a part of critical areas protection as Site Potential Tree Height or the role played by forest protection.

In an effort to minimize impacts of development at the landscape scale, some jurisdictions impose clearing limits to minimize degradation of habitat and improve stormwater management. Booth et al. (2002) summarizes evidence of various aquatic resource damages associated with conversion of forest cover to impervious area, and the limitations and problems associated with reliance on traditional stormwater mitigation efforts such as detention ponds. They note that preservation of aquatic resources in developing areas must include impervious area limits, forest retention policies, stormwater detention, riparian buffer maintenance, and protection of wetlands and unstable slopes. Specific elements (landscape level and riparian) for effective protection recommended by Booth et al. (2002) include:

- "clustered developments that protect half or more of the forest cover, preferably in headwater areas and around streams and wetlands to maintain intact riparian buffers;
- a maximum of 20 percent total impervious area, and substantially less effective impervious area through widespread reinfiltration of stormwater;
- on-site detention, realistically designed to control flow durations (not just peaks);
- riparian buffer and wetland protection zones that minimize road and utility crossings as well as overall clearing; and
- no construction on steep or unstable slopes."

Finally, these authors stress that these recommendations rely on extrapolation, model results, and judgment and thus the specific values (not the concepts) are still tentative.

In summary, the key to attaining effective aquatic area protection against landscape level changes is maximizing native forest cover (including continuity of riparian areas along streams and wetlands) and minimizing impervious surfaces. Where this is not possible, conventional stormwater runoff controls that detain and clean stormwater to match predevelopment conditions in terms of timing and magnitudes of flows should be employed.

Wildlife Habitat Conservation

The importance of wildlife habitat features such as nesting trees, snags, aquatic features and mature forests is well understood (Rodrick and Milner 1991; Van Horne and Wiens 1991). Equally recognized is the fact that such specific ecosystem and habitat attributes vary in usage and distribution in time and space. For example, bald eagle and red-tailed hawk nesting trees and snags blow down or rot over time, consequently, to maintain sustainable breeding populations of these State priority species, alternate trees and snags must be available (Thomas 1979; Marzluff and Ewing 2001). Likewise, other breeding and non-nesting habitats must be available for use so that all life stages for species and populations are met. Conservation of active breeding, foraging, and sheltering habitats through habitat buffers and other means is needed for species protection. However, it is equally important to provide alternative habitats for all these and all other significant needs, which may be widely dispersed within the varied ecosystems of watersheds and larger landscapes (Gutzwiller 2002; Bissonette 1997; Forman 1995).

There are two approaches to conserving species and their habitat in the literature. The first is to protect species only within clearly identified ecological reserves (i.e., tracts of land, often large in area) that are relatively homogenous in plant composition and structure regardless of adjoining land use (Frankel and Soulé 1981; Wright 1998). The second approach is to protect species across an entire region by enhancing the quality of existing habitat and by providing for all important wildlife needs (Franklin 1993; Morrison et al. 1998). Both approaches require the protection of ecological functions, ecological composition, and adequate habitat structure.

Wildlife habitat conservation has been grouped into several internal (site-specific) and external (contextual) habitat considerations. Internal considerations include:

1. The structural diversity (both vertically and horizontally) of the habitat. Vertical diversity is derived from the amount and distribution of vegetation and other structural elements in various zones ranging from below the ground to the tops of the tallest trees. Horizontal diversity is determined by the size and distribution of vegetation patches across the landscape. Greater structural diversity generally increases the diversity of a given area's wildlife (Trevithic et al. 2001). A wetland with a patch of trees or open water is generally more valuable for habitat than a uniform stand of Douglas fir in a plantation. A forest with a well-developed understory is generally more valuable than a uniform stand of cattails or spirea, or a dense forest with no understory.

2. The edge conditions of the habitat area. Edges (ecotones) are used by relatively greater numbers of species, which may be harmful or beneficial to native species depending on the taxa adapted to and occupying the edge (Lidicker and Koenig 1996). An area, such as a natural burn area, with a mosaic of habitat types that provide an undulating edge is more valuable to wildlife than an area of equal size but with a linear edge. Increased amounts of edge along wetlands or streams, provided they have adequate buffers, increase the value to wildlife species. In contrast, a terrestrial area adjacent to human habitation and certain land uses (e.g., grazing, farming) may have greater numbers of species, but typically they will be square-edged and contain harmful exotic species and aggressive native species (Richter and Azous 2000). Edges in human-created and occupied environments, although diverse in species, are often dominated by generalist, competitive synanthropic (human associated, tolerant) edge species and fewer interior core species. Human edges are often straight and

abrupt with little transition. In natural environments, edges are generally gradual transition zones, non-linear, and characterized by higher species diversity than areas along straight edges (Meffe and Carroll 1994). In aquatic systems, convoluted edges include coves, lobes, and peninsulas that enable better positive interactions between aquatic and terrestrial organisms than straight edges by; (1) increasing the length of beneficial transition habitat (the productive shallow shoreline); and (2) by facilitating the dispersal of organisms that have biphasic life stages (invertebrates, amphibians) between aquatic and terrestrial systems (Meffe and Carroll 1994). Edge processes near human development may include "increased wind; reduced humidity; increased predation on amphibians, birds, and small mammals; increased predation and parasitism on bird nests; increased exposure to invasive plants; and increased clearing, pruning, and trampling of native vegetation."

3. The presence of snags and large trees in the habitat area. Snags serve many important functions for wildlife, especially nesting, cover, and food sources for cavity-nesting birds and mammals (see further discussion on snags below in Priority Habitats section). If snags are removed for safety reasons, leaving stumps, even decaying stumps, only a few feet high can be beneficial to wildlife.

4. The presence of adequate numbers of downed trees. Deadfall, or downed logs also serve a number of important functions for some wildlife species, particularly in or near streams and wetlands. Coarse woody debris, including logs, are critical elements of healthy, productive, and biologically diverse forests (Bull 2002). Thomas (1979) identified 179 vertebrate species that use coarse woody debris (snags and down wood) in the Blue Mountains of Oregon and Washington. Loss of rotten-log communities may affect some woodpeckers, such as the pileated woodpecker, because of the resultant decline in carpenter ants (Marzluff and Ewing 2001). Logs may also contain moisture, and the cool microclimate may protect certain species during short-term droughts.

5. The proximity of the habitat area to water. Water is one of the essential components of habitat. Wetlands and riparian areas are especially important for wildlife as they may provide all survival needs in close proximity to each other (Kaufman et al. 2001), including year-round surface water. Their often high vegetation productivity of grasses, herbs and shrubs provide food sources for a multitude of invertebrate and vertebrates herbivores. In turn, these animals attract carnivores and omnivores. The diverse vegetation structure of wetlands also provides cover from predators and a unique and benign microclimate that is often warmer in winter and cooler in the summer than adjoining uplands and other terrestrial area. Collectively, these traits are optimum for successful reproduction, and therefore the high number of wetland-associated species.

External considerations include:

1. The size of the habitat area. Generally, large patches of a given habitat type are more valuable than small patches. Optimal patch size in western Washington may be around 75-100 acres (30-40 ha). Donnelly (2002) found that areas greater than 75 acres are useful for many native birds, but specific species do have thresholds of occurrence that are related to amount and configuration of the forested habitat. Most native forest species were present at sites larger than 42 ha in the urbanizing area around Seattle. However, the case can be made to protect relatively smaller patches (e.g., 5-20 acres, or 2-8 ha) of diverse vegetation that are more widely distributed across the urban landscape, because these areas may be

"stepping stones" between larger areas for some birds that persist in smaller patches (Fahrig and Merriam 1994). Woodlots surrounded by urban development, for example, often serve as "island refuges" for species that would otherwise not be found in residential neighborhoods.

2. Linkage (e.g., a corridor) to otherwise isolated natural areas, parks, preserves, open spaces, or large tracts of land designated for long-term forestry. Corridors are valuable in facilitating movement of animals between essential breeding, feeding, and roosting habitat and in minimizing negative attributes (e.g., reduced numbers, inbreeding, greater vulnerability to local extinction) of isolated populations. Although corridors may have negative effects, such as providing a pathway for the transmittal of invasive weeds or diseases (Hess 1996), the positive effects of corridors are believed to outweigh the potential negative effects. Riparian areas provide especially important movement corridors in urban-rural landscapes.

3. Whether or not the habitat area serves as a buffer, or is surrounded by habitat buffer. Buffers are especially important when human activity may affect the area. Buffers may be visual or auditory, and they may also serve to act as a barrier for unwanted species. For example, a buffer would have increased value if it were effective in keeping domestic cats away from nesting birds (Simberloff and Cox 1987) or in keeping mice and rats away from bird eggs.

4. The state and quality of the surrounding habitat and urban areas. The wildlife in the area may be positively or negatively affected by adjacent habitat or land uses. An area adjacent to an existing park with native vegetation will be more valuable to wildlife than a similar area adjacent to commercial or industrial development.

A Puget Sound area study by Marzluff and Donnelly (2002) indicates that there are three main steps to adequately conserve native forest species in an urban environment:

(1) limit urban development to 52 percent of the landscape;

(2) keep at least 64 percent of the remaining forest aggregated, creating stands greater than 42 ha wherever possible; and

(3) maintain at least 23 percent conifers in the canopy and maintain tree density above an average of 9.8/ha. Tree density in individual yards should vary around this average.

Results from another Puget Sound study by Rohila and Marzluff (2002) suggest that if at least 30 percent of forest is retained in settled areas, and high live-tree density and large tree diameters are maintained, cavity-nesting birds may be maintained for up to several decades. They recommend that forest be retained in the largest patches possible (30 ha or greater), and that the smallest average forest patch size does not fall below 3 ha. Rohila and Marzluff (2002) also provide recommendations for snag retention.

Active restoration of wildlife habitat should not be underestimated for stemming and reversing the loss of wildlife. Strategic land use planning which examines temporal patterns of human demography and dispersal as well as the spatial distribution of habitat and in which conservation of target species are protected, restored, and scientifically managed, can significantly contribute to the persistence and recovery of certain populations (Scott et al. 2001).

Key Wildlife Habitats

Old-Growth and Mature Forest Habitats

Old-growth forest and mature forests are defined in slightly different ways.. Timber growers and other commercial interests define old growth and mature forests via timber production criteria such as the amount of usable clear lumber produced in a given timber stand. Most authors use ecological attributes instead of production measures to define and differentiate old growth and mature forest areas and agree that old growth and mature forests share attributes (Marcot et al. 1991; Franklin and Spies 1991). Marcot et al (1991) reviews old growth inventories performed by a number of authors who use these various definitions and presents the case for use of accepted ecologically based definitions. They illustrate the importance of definition for inventorying (and potentially protecting) old-growth and mature forests, and recommend that inventories are based on measurable physical attributes, are map-based, and that adopted definitions be part of a system of coherent classification within various ecological stages of forests.

Thomas et al. (1993) found that 312 plants, 149 invertebrates, 112 stocks of anadromous salmonids, 4 species of resident fish, and 90 terrestrial vertebrates were closely associated with old-growth forest conditions. Lehmkuhl and Ruggiero (1991) performed an extinction risk assessment for 94 vertebrate species dependent on late-successional forest (old-growth and mature forest). They report that 68 of these species have primary dependence on late-successional forest, and the most at-risk species for local extinctions include several species of salamanders and many small mammals such as voles, moles, and squirrels. Also at risk are bald eagles, northern goshawks, pileated woodpecker, northern spotted owl, Vaux's swift, blue grouse, band-tailed pigeon, fisher, marten, and other bird and mammal species.   All of these species except the fisher, which was historically extirpated from the region, occur within Snohomish County. Bald eagles, northern goshawks, band-tailed pigeons, and Vaux swifts all are regular inhabitants within and around Snohomish County's urban growth areas.

Old-growth forests, and to a lesser extent, mature forests, have complex structural components and stand attributes that are quite different from any other type of forest (Franklin and Spies 1991). These important structural components, such as snags and down wood, and stand attributes, such as multi-storied and deep canopy, foster the distinctive communities found in old-growth forests (Franklin and Spies 1991). Manuwal (1991) found that old-growth stands have the highest densities of very large snags, and mature stands have the highest densities of large hardwood snags, such as bigleaf maple and cottonwood.

Thomas et al. (1993), Manuwal (1991) and Johnson and O'Neil (2001) quantify the overriding importance of snags and other habitat features to a wide range of terrestrial and aquatic wildlife. Additionally, Manuwal (1991) points out that winter old-growth habitat is particularly important because of the relatively large percentage of permanent residents in Douglas-fir forests.

Much remains unknown about the old-growth ecosystem (Franklin and Spies 1991), and much remains to be learned about the value of mature forests. Mature forests that have grown up after an old-growth forest was destroyed from natural disturbance (e.g., fire) will have greater complexity associated with it because of legacies from the previous forest, such as snags and down logs, than will a managed second-growth forest (Franklin and Spies 1991). Consequently, naturally formed mature forests will have greater value for many species of wildlife (woodpeckers, amphibians, etc.), whereas the effects on hydrology, for example, may not be significantly different between types of mature forest.

Wildlife Corridors

Human population growth and urbanizing pressures has greatly altered the wildlife habitat areas of the Puget Sound (Naiman et al. 1992, May et al. 1997) and posed significant challenges for land managers and regulatory agencies that strive to balance land use with species and habitat preservation. The Puget Sound landscape that was historically characterized by a matrix of human development within expansive natural environments in much of the region is now characterized in just the opposite way as natural environments embedded within a matrix of human development. Growth and human development has resulted in the reduction and loss of natural habitats, altered the structure and function of naturally occurring habitats, and fragmented many habitats into small isolated habitat patches and areas.

One approach that land managers and regulatory agencies have implemented to alleviate impacts on wildlife habitats and species within human-influenced environments includes the establishment of wildlife habitat corridors. Habitat corridors are contiguous, vegetated, dispersal conduits of variable length and width that connect isolated habitat patches to other patches or larger landscape habitat components (Manuwal 1991).

Most definitions of wildlife corridors in the literature define corridors as dispersal conduits that link isolated habitat patches (Rosenberg et. al. 1997). Corridors, if wide enough and vegetated, may also provide habitat where resident organisms live and reproduce (Rosenberg et. al. 1997; Noss 1993). Corridors can provide a variety of functions for flora and fauna at both the local and regional landscape spatial scale including:

- Providing a means for animals to move between habitats (home range) daily and seasonally (Noss 1993);
- Enabling animals to disperse from one patch to another;
- Reducing species extinction rates by ensuring that populations or individuals are not isolated from others in the landscape.
- Guarding against detrimental genetic effects (inbreeding depression and random genetic drift);
- Providing increased foraging habitat for a variety of species;
- Providing predator escape cover for animals as they move between patches; and
- Providing an avenue for vegetative communities to maintain reproduction viability and colonize new areas (Rosenberg et. al. 1997).

A recurring theme by Noss (1993) is that corridors should be as wide as possible while taking into consideration habitat structure and quality within the corridor, as well as the surrounding habitat, human use patterns, and species expected to use the corridor.

At the Pacific Northwest landscape scale, presence of adequate corridors may decrease the level of genetic variation among populations, or provide a means for fire or other physical disturbances to spread within the landscape. Although there are potential concerns to corridors in specific landscape situations, in most areas of the natural landscape, habitats were historically connected and many identified potential corridor disadvantages were in effect at that time. Therefore, species evolved and habitats were influenced by some of the potential corridor shortcomings. Corridor establishment attempts to mimic, in a managed landscape, the natural biologic processes that historically occurred. Beier and Noss (1998) reviewed several studies on wildlife corridors and found that "only about 12 studies allow meaningful inferences of conservation value, 10 of which offer persuasive evidence that corridors provide sufficient connectivity to improve the viability of populations in habitats connected by corridors."

Thus, given the constraints of increased human growth and development, corridor establishment has been generally accepted to provide more ecological advantages than disadvantages, and corridors are considered an essential component for promoting ecological processes in landscapes (Dawson 1994).

Much remains uncertain and debated about how to design corridors so they funnel and not trap those species they are intended to serve. Similarly, buffers must be designed so they adequately shield native species from the negative impacts of fragmentation (Marzluff and Ewing 2001).

The criteria for establishing corridors and the characteristics of the corridors (length, width, and vegetative type) vary significantly depending on land management and ecosystem objectives. Overall, the larger the corridor, the greater ecological value gained. Because there are often financial and regulatory constraints involved in establishing expansive corridors, large corridors are not always practicable. Therefore, because various species have specific life needs and movement patterns, much of the scientific literature supports identifying criteria and characteristics of proposed corridors based on the needs of a specific species or species guild that are in danger of isolation.

To preserve biodiversity in fragmented landscapes, most authors (Davis and Glick 1978; Soule 1991; Shafer 1997; all as cited in Marzluff and Ewing 2001) recommend either establishing corridors among native patches or buffering native patches with native habitat to increase their size and amount of interior area. Marzluff and Ewing (2001) contend that the design and establishment of a system of native vegetation reserves and the maintenance and restoration of ecological function in those reserves are imperative for conserving biodiversity in urban landscapes.

Reserves must be large enough to allow a great enough core size so that they are not population sinks (Marzluff and Ewing 2001). Authors such as Davis and Glick (1978), Soule (1991), and Shafer (1997) "uniformly recommend that (1) the area and numbers of reserves be maximized; (2) the amount of edge and degree of fragmentation within reserves be minimized; (3) the connectivity between reserves be maximized; (4) buffers be maintained around reserves; and (5) the scale of reserve planning be expanded beyond the local area to include entire watersheds and bioregions" (Marzluff and Ewing 2001).

Natural riparian corridors provide an extremely wide range of highly valuable functions. They are important habitats in their own right for a wide range of wildlife (Knutson and Naef 1997). They are also considered essential for sustaining wild fish populations (Naiman et al. 1993). Naiman et al. (1993) notes that riparian areas are the most diverse, dynamic, and complex biophysical habitats on the terrestrial portion of the Earth.

Streams and Wetlands as Wildlife Areas and Travel Corridors

A recent study of Snohomish County's urbanizing landscape revealed an extensive existing network of naturally vegetated travel corridors connecting wetlands and other high-value wildlife areas across forested and urbanizing landscapes of the County (Snohomish County Drainage Needs Report, December 2002). These wetland and riparian corridors follow and delineate existing streams and wetlands in Snohomish County, and exist largely because of riparian and wetland buffer protections and requirements instituted by past Snohomish County land use restrictions. Although instituted largely to protect aquatic species and habitats, these stream and wetland buffer areas provide significant area and travel corridors to connect habitat across the County.

Natural wetland and riparian areas are biologically diverse and complex ecosystems that contain more plant, mammal, bird, and amphibian species than the surrounding upland areas (Kauffman et al. 2001). Wildlife use riparian corridors more than any other type of habitat (Thomas et al. 1979). Riparian areas provide several functions important to wildlife, including:

1. Food and Water
2. Protective Cover
3. Transportation and movement corridors connecting diverse habitat areas
4. Provision of appropriate microclimate conditions

The ability of the wetlands and riparian corridors to attract and support fish and wildlife is dependent on the structural and functional integrity of the aquatic, riparian and upland ecosystems (Knutson and Naef 1997). The influence riparian areas exert on a stream is related to the size of the stream, its location in the watershed, the hydrologic pattern and local landforms (Naiman et al. 1992). Wildlife are attracted to riparian areas because of the abundance of food sources, cover, and proximity of drinking water. Access to water is critical for both riparian-dependent wildlife and for many upland species.

Riparian areas are especially important areas during breeding season and provide wildlife with an energy-efficient habitat for rearing young due to the close proximity of food, water and cover, thereby minimizing energy expenditures by the adults and young. The greater availability of water to plants in riparian areas increases plant biomass production, providing a complex and highly productive food web. Seeds, herbaceous vegetation and fruits, aquatic and terrestrial insects, and fungi are plentiful (Thomas et al. 1979; Knutson and Naef 1997).

Riparian areas also provide predators with an abundance of prey species (Knutson and Naef 1997). Riparian vegetation in the form of grasses, shrubs, trees and other plants provides wildlife habitat for reproduction, nesting, roosting, foraging and protection from the weather and from competitive and predatory species. Riparian areas often contain unique plant communities, both in composition and structural complexity (Kauffman et al. 2001). Structural complexity exists when there is a diversity of plant species, multiple canopy layers (e.g., deciduous vs. coniferous; shrubs vs. trees), and snags and downed woody material (Thomas et al. 1979; Knutson and Naef 1997; Kauffman et al. 2001).

Many wildlife species are associated with specific plant communities; some require a certain age (e.g., old growth or pioneer species). Riparian areas exhibit a high diversity of wildlife species because of the complexity and diversity of habitat they provide for obligate (i.e., riparian dependant) riparian species, species seeking edge habitat, and species associated with early successional plant communities (Naiman et al. 2000). Table 3.5 shows a summary of this information for the coastal eco-region of the Pacific Northwest.

Table 3.5 Numbers, by Taxonomic Class, of native Upland and Riparian Obligate Species as Compared to all Species in the Pacific Coastal Eco-Region

TAXON	RIPARIAN ZONE OBLIGATE SPECIES	TOTAL # SPECIES	% RIPARIAN OBLIGATE SPECIES
AMPHIBIANS	18	30	60
REPTILES	3	19	16
BIRDS	78	231	34
MAMMALS	13	107	12
TOTAL	112	387	29

(Adapted from Kelsey and West 1998)

In addition to *riparian obligates*, riparian zones also support *riparian generalists* or species that use both riparian and upland habitats. Riparian corridors also serve as migration or dispersal corridors for a variety of species (Kelsey and West 1998). In general, riparian obligates depend on certain habitat characteristics associated with stream size. The riparian wildlife communities that large rivers support can differ greatly from those associated with small streams.

Wildlife species also respond to habitat characteristics associated with forest successional stage that is largely determined by the type, frequency, duration, and severity of disturbance (Naiman et al. 2000). For example, the presence and distribution of snags and LWD piles in riparian zones has a positive influence on avian community diversity as well as on the species richness and abundance of small mammals. Some species of invertebrates, birds and mammals rely on snags (standing dead trees) and downed and dead wood for a portion of their life history. Downed and dead woody material in various stages of decay provides diversity in the environment and is of varying significance for wildlife habitat (Thomas et al. 1979). Much of the biodiversity and productivity of the riparian area would disappear without this woody debris accumulation (Naiman et al. 1992).

The linear nature of riparian areas maximizes the development of edge habitat, an area where two different plant communities, successional stages, or vegetative conditions meet (Thomas et al. 1979). Some species benefit from the availability of edge habitat because edges contain plant communities that are characteristics to each adjoining habitat (Knutson and Naef 1997). Although edge habitat can promote high wildlife diversity, it can also have a negative impact on some species associated with interior portions of the riparian areas notably by providing increased competition for nesting sites, and increased access by edge predators and nest parasites such as cowbirds.

Many wildlife populations rely on their ability to move between different types of habitat along riparian corridors, especially for species that would not otherwise cross large openings. Riparian corridors, because of their linear shape, enable movement of wildlife between habitat patches (Thomas et al. 1979; Noss 1993). Dispersal and establishment of new territories for feeding and breeding is important for many species. This allows for an exchange of genetic material between species populations and is critical for resilience to disease and other negative impacts. At least 95 percent of all terrestrial species in North America depend on migration corridors, many of which are also riparian corridors. Riparian corridors also play a potentially important role within landscapes as corridors for plant dispersal and may be an important source of most colonists through the landscape.

Based on current research, 85% of all Washington's terrestrial vertebrates (birds, mammals, reptiles, and amphibians) utilize the stream-riparian ecosystem during some or all of their life histories (Knutson and Naef 1997). A diverse array of wildlife species utilize the stream and riparian forest for food, water, shelter, nesting, rearing, and as a migration corridor.

Generally, most wildlife researchers advocate preserving or restoring as wide a riparian corridor as possible, but most agree that even a narrow buffer will provide some habitat for most species. It is important to remember that any loss of biodiversity can have significant negative impacts on entire ecosystems. As discussed earlier in this chapter, salmonids play an integral role in the stream-riparian ecosystems of the Pacific Northwest. The complex linkages between salmonids and other species in this ecosystem is not fully understood. This must be recognized when designing riparian buffers so as to support as many interconnected species as possible and not to narrowly focus just on fish habitat.

The presence of travel corridors for wildlife species leading to wetlands or to upland habitat is critical. Relatively undisturbed migration routes between a wetland and upland feeding and hibernation sites are important for many amphibian species. Moreover, dispersal routes for recolonization are critical when populations are eliminated by random processes including drought, disease, or pollution, or when populations produce insufficient offspring to permanently occupy a site. Finally, inbreeding is minimized when the wildlife within a wetland are members of a population that extends across several wetlands.

Threatened and Endangered Species

There are 38 species of animals listed by the USFWS (2003) as threatened or endangered in Washington (not including whales and non nesting sea turtles). There are a total of ten federal and state listed threatened and endangered wildlife species known or presumed to exist in Snohomish County. Wildlife occurring in Snohomish County and listed as threatened or endangered by state or federal agencies are listed in Table 3.6 along with several candidate species. Federally listed endangered species for which habitat protections are required are described below. Other state and federally listed species in the County include wetland species (that will be protected by wetland provisions of the critical area regulations); species that occur only in the eastern forested portions of the County where protections are provided by the Timber Fish and Wildlife (TFW) agreement; and marine species not found in shallow nearshore areas. A number of other species that are state candidate or species of concern can occur in the lowlands of Snohomish County (see Table 3.6). A summary of the presence and habitat dependencies of state listed endangered species is included below.

Bald Eagle

Bald eagles are predominantly found along the shores of salt water, lakes, and rivers. Breeding bald eagles need large trees near open water and low human disturbance. In Washington, nearly all bald eagle nests (99 percent) are within a mile of a lake, river, or marine shoreline. Territory size and configuration are influenced by a variety of habitat characteristics, including availability and location of large super dominant trees for nesting and perch trees for foraging, quality of foraging habitat, and distance of nests from waters supporting adequate food supplies.

Bald eagles are not old growth obligates, but they do need large trees that can support their massive nests. Because nesting territories are generally used in successive years, eagles select nesting sites that have other large trees nearby in case a replacement nest is needed. In Washington, courtship and nest building activities generally begin in January and February. Egg laying usually begins in March, with eaglets hatching by late April. Eaglets usually fledge in mid July and often remain in the vicinity of the nest for another month.

Eagles often depend on dead or weakened prey, and their diet may vary locally and seasonally. Various carrion—including spawned salmon taken from gravel bars along wide, braided river stretches—are important food items during fall and winter. Waterfowl often are taken as well. Anadromous and warmwater fishes, small mammals, carrion, and seabirds are consumed during the breeding season.

In Washington, bald eagles nest primarily to the west of the Cascade Mountains, and frequently along shorelines of Puget Sound. Wintering populations are found throughout the Puget Sound region, and are known to concentrate along rivers with known salmon runs, such as the Skagit River. There are many known, active bald eagle nests in Snohomish County (WDFW 2003). A number of these are located in shoreline areas of Puget Sound. Others are found in forested areas near lakes and rivers. In addition, seasonal concentrations are found, especially along the Skagit delta and river during the winter attracted by wintering waterfowl and salmon runs. Locations of known bald eagle nests and winter roosts are maintained by the Washington Department of Fish and Wildlife in the Priority Habitat and Species (PHS) database.

Bald eagle life history, habitat requirements, and management recommendations are also summarized in WDFW's Priority Habitat and Species Management Recommendations for Birds and the Recovery Plan for the Pacific Bald Eagle (USFWS 1986).

Marbled Murrelet

The marbled murrelet, a small seabird that nests in the coastal, old growth forests of the Pacific Northwest, inhabits the Pacific coast of North America from the Bering Sea to central California. In contrast to other seabirds, murrelets do not form dense colonies and may fly 75 km (46.6 miles) or more inland to nest, generally in older coniferous forests. They are more commonly found inland during the summer breeding season, but make daily trips to the to sea to gather food, primarily fish and invertebrates, and have been detected in forests throughout the year. When not nesting, the birds live at sea, spending their days feeding and then moving several miles offshore at night.

The breeding season of the marbled murrelet generally begins in April, with most egg laying occurring in late May and early June. Peak hatching occurs in July after a 27 to 30 day incubation. Chicks remain in the nest and are fed by both parents. By the end of August, chicks have fledged and dispersed from nesting areas (Hamer and Nelson 1995). The marbled murrelet differs from other seabirds in that its primary nesting habitat is old growth coniferous forest within 50 miles of the coast. The murrelets typically appear to exhibit high fidelity to their nesting areas and have been observed in forest stands for up to 20 years. Marbled murrelets have not been known to nest in other habitats, such as alpine forests, bog forests, or scrub vegetation.

At sea, foraging murrelets are usually found as widely spaced pairs. In some instances murrelets form or join flocks that are often associated with river plumes and currents. These flocks may contain sizable portions of local populations. Marbled murrelets use Puget Sound for foraging and overwintering. During the breeding season, their nesting habitat is primarily restricted to old growth and late successional coniferous forests. In Snohomish County, these nesting habitats occur exclusively within the forested public lands in the eastern part of the County. All observed murrelet activity in Snohomish County has been within 50 miles of Puget Sound (WDFW 2003).

Spotted Owl

The northern spotted owl is a year-round resident throughout forested portions of western Washington at elevations generally below 5,000 feet (Thomas 1979). In the Pacific Northwest, this species typically nests in old-growth forest or mixed forests of old-growth and mature trees that are multi-layered with an overstory of large old-growth trees and one or more understory layers of smaller trees. Within these forests, spotted owls nest almost exclusively in trees in cavities or on platforms made of debris such as sticks and needles; none of the owls build their own nests.

Although the spotted owl may be found in varied structural types and age classes of forests, old-growth forest is considered to provide roosting, nesting foraging, and dispersal habitat for the species. The Washington Administration Code (222-16-085) has defined suitable spotted owl habitat for nesting, roosting, foraging, and dispersal. This habitat consists of the following characteristics: (1) a canopy closure of 60 percent or more and a layered, multispecies canopy where 50 percent or more of the canopy closure is provided by large overstory trees; (2) three or more snags or trees 20 inches dbh or larger and 16 feet or more in height per acre with various deformities such as large cavities, broken tops, dwarf mistletoe infections, and other indications of decadence; and (3) more than two fallen trees 20 inches dbh or greater per acre and other woody debris on the ground.

Spotted owls typically forage at night by sitting on elevated perches and diving on their prey, which includes a variety of mammals (especially arboreal and semi-arboreal), birds, and insects. Established pairs typically remain in the same territories from year to year, and foraging areas may exceed 2,470 acres (1,000 hectares). Forsman (1981) documented that foraging areas ranged from 1,350 to 8,350 acres (546-3,379 ha). Territory sizes are 100-340 acres (40-138 ha) with an average of 230 acres (93 ha).

Forest management activities, particularly the removal of old-growth forest and disturbance of nest sites, are believed to be the single greatest factor for spotted owl population declines (Forsman 1981).

Sandhill Crane

Sandhill Cranes are primarily birds of open freshwater wetlands and shallow marshes. Habitats along migration routes tend to be large, open palustrine and riparian wetlands near agricultural areas, while wintering habitats include riparian wetlands, wet meadows, seasonal lakes, and pastures. Sandhill Cranes are omnivorous, feeding on a wide variety of plant materials (including waste grains) and small vertebrates and invertebrates, both on land and in shallow wetlands. The leading threat to the species is the loss and degradation of wetland habitats, especially ecological and hydrological changes in important staging areas.

Grizzly Bear

Only a "remnant" population of Grizzly Bears remains in the North Cascades, incapable of enduring without active recovery efforts, including possible augmentation with bears from other areas. Study of this remote habitat indicates that this ecosystem is capable of supporting a self-sustaining population of grizzlies. The US Fish and Wildlife Service determined in 1991 that this population was warranted for listing as "endangered." However, workload on other species in greater danger of extinction has delayed the Service from proposing "endangered" status for these populations. A recovery plan for North Cascades was approved in 1997, but has not been implemented due to lack of funds (USFWS 2004).

Gray Wolf

Although there have been occasional reports of individual wolves in Washington, no documented wolf breeding pairs or packs currently are known in this state. Sightings here so far are believed to involve lone wolves from Canada and wolf/dog hybrids, which have been released into the wild. Wolves are highly adaptable and can survive in a variety of habitats, although they prefer relatively flat, open areas such as river valleys and basins. The gray wolf is listed as both a federal and a state endangered species. Wolves essentially were eliminated in Washington by the 1930s through hunting, trapping and poisoning.

Table 3.6
WDFW Vertebrate Species of Concern in Snohomish County

Current through July 1, 2005

COMMON NAME	SCIENTIFIC NAME	ANIMAL TYPE	FEDERAL STATUS	STATE STATUS
ALEUTIAN CANADA GOOSE	*BRANTA CANADENSIS LEUCOPAREIA*	Bird	FCo	ST
AMERICAN PEREGRINE FALCON	*FALCO PEREGRINUS ANATUM*	Bird	FCo	SS
BALD EAGLE	*HALIAEETUS LEUCOCEPHALUS*	Bird	FT	ST
BELLER'S GROUND BEETLE	*AGONUM BELLERI*	Beetle	FCo	SC
BLACK-BACKED WOODPECKER	*PICOIDES ARCTICUS*	Bird	none	SC
BRANDT'S CORMORANT	*PHALACROCORAX PENICILLATUS*	Bird	none	SC
BULL TROUT (COASTAL/PUGET SOUND)	*SALVELINUS CONFLUENTUS*	Fish	FT	SC
CASSIN'S AUKLET	*PTYCHORAMPHUS ALEUTICUS*	Bird	FCo	SC
CHINOOK SALMON (PUGET SOUND)	*ONCORHYNCHUS TSHAWYTSCHA*	Fish	FT	SC
COMMON LOON	*GAVIA IMMER*	Bird	none	SS
COMMON MURRE	*URIA AALGE*	Bird	none	SC
EULACHON	*THALEICHTHYS PACIFICUS*	Fish	FC	SC
FISHER	*MARTES PENNANTI*	Mammal	FCo	SE
GOLDEN EAGLE	*AQUILA CHRYSAETOS*	Bird	none	SC
GRAY WHALE	*ESCHRICHTIUS ROBUSTUS*	Mammal	none	SS
GRAY WOLF	*CANIS LUPUS*	Mammal	FT	SE

GRIZZLY BEAR	*URSUS ARCTOS*	Mammal	FT	SE
HARLEQUIN DUCK	*HISTRIONICUS HISTRIONICUS*	Bird	none	none
KEEN'S MYOTIS	*MYOTIS KEENII*	Mammal	none	SC
KILLER WHALE	ORCINUS ORCA	Mammal	none	SE
LAKE CHUB (Twin Lake, SnoCo)	*COUESIUS PLUMBEUS*	Fish	none	SC
LYNX (Suiattle R drainage)	LYNX CANADENSIS	Mammal	FT	ST
MARBLED MURRELET	*BRACHYRAMPHUS MARMORATUS*	Bird	FT	ST
MERLIN	*FALCO COLUMBARIUS*	Bird	none	SC
NORTHERN GOSHAWK	*ACCIPITER GENTILIS*	Bird	FCo	SC
OLYMPIC MUDMINNOW (sites in Snohomish County)	*NOVUMBRA HUBBSI*	Fish	none	SS
OREGON SPOTTED FROG	*RANA PRETIOSA*	Amphibian	FC	SE
PACIFIC TOWNSEND'S BIG-EARED BAT	*CORYHORHINUS TOWNSENDII TOWNSENDII*	Mammal	FCo	SC
PEALE'S PEREGRINE FALCON	*FALCO PEREGRINUS PEALEI*	Bird	FCo	SS
PEREGRINE FALCON	*FALCO PEREGRINUS*	Bird	FCo	SS
PILEATED WOODPECKER	*DRYOCOPUS PILEATUS*	Bird	none	SC
PURPLE MARTIN	*PROGNE SUBIS*	Bird	none	SC
RIVER LAMPREY	*LAMPETRA AYRESI*	Fish	FCo	SC
SANDHILL CRANE	*GRUS CANADENSIS*	Bird	none	SE
SPOTTED OWL	*STRIX OCCIDENTALIS*	Bird	FT	SE
STELLER SEA LION	*EUMETOPIAS JUBATUS*	Mammal	FT	ST
TAILED FROG	*ASCAPHUS MONTANUS*	Amphibian	none	SC
TOWNSEND'S BIG-EARED BAT	*CORYHORHINUS TOWNSENDII*	Mammal	FCo	SC
VAUX'S SWIFT	*CHAETURA VAUXI*	Bird	none	SC
WESTERN GREBE	*AECHMOPHORUS OCCIDENTALIS*	Bird	none	SC
WESTERN POND TURTLE	*CLEMMYS MARMORATA*	Reptile	FCo	SE
WESTERN TOAD	*BUFO BOREAS*	Amphibian	FCo	SC
WOLVERINE	*GULO GULO*	Mammal	FCo	SC
YELLOW-BILLED CUCKOO (extirpated?)	*COCCYZUS AMERICANUS*	Bird	FC	SC

Status
E = Endangered
T = Threatened
S = Sensitive
C = Candidate
SC = Species of concern

Table 3.7 Summary of Studies on Wildlife Habitat Provided by Buffers.

AUTHORS	DATE	WIDTH	COMMENTS
Allen	1982	328 – 590 feet (100 – 180 m)	Mink use: generally concentrated within 330 feet (100 m) of water but will use upland habitats up to 590 feet (180 m) DISTANT
Burke and Gibbons	1995	240 feet (73 m): 90% 902 feet (275 m): 100%	Buffer to encompass % nesting and hibernation of turtles in North Carolina

Castelle et al.	1992	197 – 295 feet (60 – 90 m): Western Washington	Range for all species they noted.
Castelle et al.	1992	263 feet (80 m) avg. -590 feet (180 m)	Wood duck nesting locations from wetland edge (non-Washington data)
Castelle et al.	1992	328 feet (100 m): Western Washington	Distance of beaver use of upland habitats from water edge
Chase et al.	1995	98 feet (30 m) or more	100 feet (30 m) would be "adequate"; buffers larger than 100 feet needed to meet habitat needs, including breeding for birds and some mammals
Cross	1985	220 feet (67 m)	Forested "leave-strips" for small mammal richness adjacent to streams in SW Oregon
Desbonnet et al.	1994	49 – 98 feet (15 – 30 m): low intensity 98 – 328 feet (30 – 100 m): high intensity	Variable buffer widths using adjacent land uses as decision-making criteria
Fischer et al.	2000	98 feet (30 m) minimum	Literature review; majority of literature cited recommends buffer widths of 330 feet (100 m) for reptiles, amphibians, birds, and mammals
Foster et al.	1984	98 feet (30 m): 68% of nests) 312 feet (95 m): 95% of nests	Waterfowl breeding use of wetlands in the Columbia Basin greatest in smaller (<1 acre [0.4 ha]) wetlands; 68% of waterfowl nests within 100 feet (30 m) of wetland edge; to encompass 95% of waterfowl nests would require 310 feet (95 m) of buffer
Groffman et al.	1991	197 - 328 feet (60 - 100 m)	For most wildlife needs
Groffman et al.	1991	328 feet (100 m)	Neotropical migratory bird species
Howard and Allen	1989	197 feet (60 m)	For most wildlife needs
McMillan	2000	98 – 328 feet (30 – 100 m)	Based on a synthesis of literature
Milligan	1985	49 feet (15 m)	Bird species diversity strongly correlated with the percentage of the wetland boundary buffered by at least 50 feet (15 m) of tree and shrub vegetation
Norman	1996	164 feet (50 m)	To protect wetland functions; more buffer may be required for "sensitive wildlife species"

Ostergaard	2001	3,280 feet (1,000 m)	Forested habitat surrounding stormwater ponds, related to native amphibian richness
Richter	1996	3,280 feet (1,000 m)	Literature review and synthesis
Richter	1996	3,280 feet (1,000 m)	Native amphibian use
Richter and Azous	2001b	1,680 feet (512 m)	Distance from wetland edge necessary to include all bird richness in Puget Sound lowland wetlands
Richter and Azous	2001c	1,640 feet (500 m): 60%	Highest small-mammal richness when 60% of first 1,640 feet (500 m) of buffer was forest habitat
Semlitsch	1998	228 – 411 feet (69.6 - 125.3 m) 539 feet (164.3 m) for 95% of all species	Six species of adult salamanders and two species of juveniles; mean distance from wetland edge was 228 feet (juveniles) – 411 feet (adults). To incorporate 95% of all species, buffer mean would have to be 539 feet
Semlitsch	1998	1,969 feet (600 m)	Salamanders
Short and Cooper	1985	164 – 328 feet (50 – 100 m)	164 feet (50 m) for foraging
Temple and Cary	1988	> 656 feet (200 m): 70% success 328 – 656 feet (100 – 200 m): 58% success < 328 feet (100 m): 18% success	Nesting success rates for interior-dwelling forest birds related to distance into the interior of a forest from the forest edge

Source: Sheldon, D., T. Hruby, P. Johnson, K. Harper, A. McMillan, S. Stanley, E. Stockdale. August 2003 Draft. Freshwater Wetlands in Washington State Volume 1: A Synthesis of the Science. Washington State Department of Ecology Publication # 03-06-016.

Table 3.8 Western Washington Vertebrate Wildlife Associated with Riparian Habitat

Amphibians associated with Western Washington rivers & streams

Species	Comments
Northwestern Salamander	
Long-toed Salamander	
Cope's Giant Salamander	
Pacific Giant Salamander	
Olympic Torrent Salamander	
Columbia Torrent Salamander	
Southern Torrent Salamander	
Cascade Torrent Salamander	
Rough-skinned Newt	
Dunn's Salamander	
Van Dyke's Salamander	
Tailed Frog	
Red-legged Frog	
Bullfrog	
Green Frog	

Birds associated with Western Washington rivers & streams

Species	Comments
Common Loon	
Yellow-billed Loon	
Pied-billed Grebe	
Horned Grebe	
Red-necked Grebe	
Eared Grebe	
Western Grebe	
Clark's Grebe	
Double-crested Cormorant	
Great Blue Heron	
Great Egret	

Snowy Egret
Green Heron
Black-crowned Night-heron
Greater White-fronted Goose
Snow Goose
Ross's Goose
Canada Goose
Mute Swan
Trumpeter Swan
Tundra Swan
Wood Duck
Gadwall
Eurasian Wigeon
American Wigeon
American Black Duck
Mallard
Blue-winged Teal
Cinnamon Teal
Northern Shoveler
Northern Pintail
Green-winged Teal
Canvasback
Redhead
Ring-necked Duck
Greater Scaup
Lesser Scaup
Harlequin Duck
Oldsquaw
Bufflehead
Common Goldeneye
Barrow's Goldeneye
Hooded Merganser
Common Merganser

Red-breasted Merganser	
Ruddy Duck	
Osprey	
Bald Eagle	
Merlin	
Peregrine Falcon	
Ruffed Grouse	
White-tailed Ptarmigan	
Blue Grouse	
Mountain Quail	
California Quail	
Virginia Rail	
Sora	
American Coot	
Sandhill Crane	
Black-bellied Plover	
American Golden-Plover	
Pacific Golden-Plover	
Snowy Plover	
Semipalmated Plover	
Killdeer	
Black Oystercatcher	**Freshwater rivers may be important for drinking and bathing.**
Greater Yellowlegs	
Lesser Yellowlegs	
Solitary Sandpiper	
Willet	
Wandering Tattler	**Freshwater rivers may be important for drinking and bathing.**
Spotted Sandpiper	
Long-billed Curlew	
Marbled Godwit	
Black Turnstone	**Freshwater rivers may be important for drinking and bathing.**

Semipalmated Sandpiper
Western Sandpiper
Least Sandpiper
Baird's Sandpiper
Pectoral Sandpiper
Dunlin
Stilt Sandpiper
Ruff
Short-billed Dowitcher
Long-billed Dowitcher
Common Snipe
Wilson's Phalarope
Red-necked Phalarope
Red Phalarope
Bonaparte's Gull
Mew Gull
Ring-billed Gull
California Gull
Herring Gull
Thayer's Gull
Western Gull
Glaucous-winged Gull
Glaucous Gull
Caspian Tern
Forster's Tern
Band-tailed Pigeon
Mourning Dove
Yellow-billed Cuckoo
Barred Owl
Black Swift
Belted Kingfisher
Pacific-slope Flycatcher
Red-eyed Vireo

Purple Martin	
Tree Swallow	
Violet-green Swallow	
Northern Rough-winged Swallow	
Bank Swallow	
Cliff Swallow	**Collect mud for nests.**
Barn Swallow	**Collect mud for nests.**
Marsh Wren	
American Dipper	
Common Yellowthroat	
Swamp Sparrow	
Red-winged Blackbird	
Yellow-headed Blackbird	**Nests regularly at a few places in Western Washington**
Mammals associated with rivers & streams	
Species	**Comments**
Vagrant Shrew	
Water Shrew	
Pacific Water Shrew	
California Myotis	**Still, open water areas for drinking; foraging over aquatic systems.**
Western Small-footed Myotis	**Still, open water areas for drinking; foraging over aquatic systems.**
Yuma Myotis	
Little Brown Myotis	
Long-legged Myotis	**Still, open water areas for drinking; foraging over aquatic systems.**
Keen's Myotis	**Still, open water areas for drinking; foraging over aquatic systems.**
Long-eared Myotis	**Use still water for drinking and forage over open water.**
Silver-haired Bat	**Still, open water for drinking; foraging over aquatic systems.**
Big Brown Bat	**Still, open water areas for drinking; foraging over aquatic systems.**
Hoary Bat	**Still open water for drinking; foraging in**

	aquatic systems. Larger open water is required because of flight speed.
Townsend's Big-eared Bat	
American Beaver	
Water Vole	**Aka Richardson’s vole (WDFW)**
Muskrat	
Nutria	
Gray Wolf	
Mink	
Northern River Otter	
Columbian White-tailed Deer	
Reptiles associated with westside Washington rivers and streams	
Species	**Comments**
Painted Turtle	
Western Pond Turtle	
Red-eared Slider Turtle	
Pacific Coast Aquatic Garter Snake	
Western Terrestrial Garter Snake	**Although called “terrestrial” -- over the majority of the range, there is a strong positive correlation with surface water (wetlands, streams, ponds, lakes).**
Common Garter Snake	

Summary

This synopsis of the scientific research indicates that the level of development and modification of habitats and species has resulted in the ongoing decline of habitat and species diversity and productivity. In part, the specified width and integrity of buffers to protect all the upland and riparian-based ecological processes (forest succession and large woody debris recruitment, stream channel migration and beach and bank erosion) needed to sustain the aquatic and terrestrial areas they encompass are often inadequate.

Wildlife habitat contains several essential elements: areas for breeding, shelter, and foraging for food and water. Some of the more important habitat areas that provide these elements include aquatic areas, riparian or upland areas adjacent to aquatic areas, old growth forests, travel corridors and habitat reserves or blocks. The research on wildlife use of riparian areas has found that 85% of all Washington's terrestrial vertebrates (birds, mammals, reptiles, and amphibians) utilize riparian area ecosystems during some or all of their life histories. Wildlife habitat requirements in riparian areas range from 15 meters up to 1000 meters (for certain amphibians – see Table 3.7). Buffers are generally in the lower range of this continuum.

Landscapes have become increasingly fragmented with human development pressure and urban expansion. Fragmentation of habitat has many detrimental effects on wildlife, including a decrease in native biodiversity, increased exposure to predators and parasites, greater disturbance due to human activity, creation of isolated populations, and restricted dispersal corridors (Saunders et al. 1991; Marzluff and Ewing 2001). When balancing the needs of human expansion and native wildlife, it is important to consider maintaining connectivity among habitats, to maintain dispersal and migration corridors, population stability, and genetic diversity. By protecting habitat for individual threatened and endangered species (and possible species or habitats of local importance to be designated in the future), a measure of protection would also be afforded for the variety of plant and animal species that inhabit natural areas of Snohomish County. In other words, all protected natural habitats, including areas protected as riparian buffers, will provide habitat for a variety of targeted (threatened or endangered) and non targeted, often common, species.

In addition, the reliance on stormwater detentions ponds to address landscape level actions, while useful, is insufficient to fully protect high water quality and simulate ecological processes (mainly forest hydrology). Efforts to mitigate impacts or restore habitats and species with artificial or unnatural approaches have not worked well, and in some cases have lead to unanticipated and costly damage repairs and ongoing maintenance because the nature of the problems were not well understood. The literature suggests that the concurrent application of both riparian-based (such as buffers or vegetated filter strips for agriculture) and landscape level actions (such as retaining forest cover, minimizing impervious surface, and enhancing stormwater controls) is necessary to minimize impacts to aquatic areas functions. The research presented in this chapter indicates that a conservation strategy for aquatic areas and wildlife habitat needs to include clear biological goals and objectives, actions to protect the most ecologically intact remaining places to achieve those goals, and restoration efforts.

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Chapter 4 – Geologically Hazardous Areas

Introduction

Geologically hazardous areas include areas associated with seismic and volcanic activity, abandoned mines, erosion, and landslide areas including steep slopes greater than 33%, which have geologic contact and seeps (Snohomish County 1996; Urquhart 1962). Geology as a scientific discipline is second only to physics in the enormity of subdivisions and sub-disciplines, consequently, a vast body of geological knowledge and literature has been developed over the years. Information for this analysis was selected, to the extent possible, for its relevance to the geology and hazards found in Snohomish County.

Seismic Hazard Areas

For purposes of this paper, and for regional consistency, magnitude (M) refers to Richter Scale rather than Modified Mercalli Scale. The Richter Scale is a logarithmic scale, which utilizes the amplitude of the seismic vibrations, or waves that are recorded on a standard seismograph to determine the magnitude or strength of the earthquake. A unit on the scale represents a ten fold increase in wave amplitude and an increase of 31.6 times the amount of energy released.

Major portions of Snohomish County are situated within the Puget Sound Lowland, an area that is subject to daily seismic activity – though most events are not detectable to the public – and is historically subject to very large earthquakes. The most recent large earthquake was the February 28, 2001 Nisqually Earthquake at M6.8. No direct deaths were associated with this earthquake, but there was substantial damage in King County and around the State Capitol building in Olympia (Hausler and Koelling 2004). Within Snohomish County, several commercial structures settled along Highway 99, and others, west of Lake Stevens were differentially racked causing laminated beam cracking. Dozens of structures suffered chimney cracking and sheet rock damage (Booth et al. 2004).

The Puget Sound Lowland lies in a larger area known as the Cascadia subduction zone. This zone comprises a series of tectonic plates that are moving with respect to one another. The Cascadia subduction zone is extremely complex in the western Washington region, involving complicated block structures within the crust and local deformation of the subducting Juan de Fuca plate. Stanley et al. (1999) has postulated that the Cascadia subduction zone could be the source for a large thrust earthquake, possibly as large as M9.0.

Two different types of seismic waves are generated from the focus or hypocenter to the surface directly via the earth's lithosphere. The first type is a body wave, which consists of a Primary wave or P compression wave and an S wave or secondary wave. The second type of seismic wave is the surface wave, which radiates from the epicenter along the surface of the earth. Surface waves consist of Love waves, which produce a lateral or sideways motion and the Rayleigh wave, which produces a rotary wave-like motion (Williams 1998).

Large intraplate earthquakes in the Puget Sound region, also known as deep Benioff zone earthquakes, are caused by the subduction of the Juan de Fuca plate beneath the North American plate, and frequent consequent intraplate crustal deformation. The Puget Sound area has been subjected to three fairly strong Benioff zone quakes in the last century that are related to intraplate crustal deformation: M7.1 Olympia, April 13, 1949; M6.5 Seattle/Tacoma, April 29, 1965; and the M6.8 Nisqually event on February 28, 2001. Several smaller quakes have also disrupted the local area and have been significant in certain areas: the M5.3 Duvall quake, May 2, 1996 affected the area of High Rock and SE Snohomish County and the M5 Maury/Vashon Island, February 28, 1995 quake impacted the liquefaction areas of Edmonds as did the aforementioned 1965 seismic event. Future Benioff zone earthquakes as large as M7.5 are expected everywhere west of the eastern shores of Puget Sound (Haugerud 2004).

Also expected are strong crustal deformation events in the Puget Sound region near faults such as the Seattle fault, which passes through the southern Seattle metropolitan area and the South Whidbey Island Fault (SWIF), which intersects the mainland in Mukilteo near Pidgeon Creek and trends Southeasterly south of the Lowell Larimer Bluff (Johnson et al. 1996). Further studies are forthcoming in the vicinity of Crystal Lake to better locate the SWIF as part of the Brightwater Project. Johnson et al. (1996) documented that the SWIF is capable of generating earthquakes of 7.0 or greater. The study or search for the SWIF involves review of the LIDAR imagery, as well as further review of the residual magnetic anomalies found in this area; additional ground trenching is also anticipated to confirm and date faults or unique geologic features (USGS 2004).

In addition, active tectonic movement has been associated with a Darrington-Devils Mountain fault that has seen movement up to a M7.5 or greater on the Richter Scale, however this fault currently lies in a rather rural portion of the County with a lower population risk (Johnson 2003).

Seismic Hazard Areas are those areas within Snohomish County that are subject to severe risk of earthquake damage as a result of ground shaking/ground motion, surface faulting, subsidence or uplift, seismically induced landsliding or settlement, soil liquefaction and tsunami or water waves and seiches. Severe risk of damage is loosely defined as the potential for damage that threatens people or property such as the structural integrity of buildings, structures, or lifeline infrastructure, rather than cosmetic or hairline cracks in the landscape. Earthquakes and their causative mechanisms have been extensively studied around the world. In the United States, the University of Buffalo, MIT, California Institute of Technology, University of Illinois and Stanford are the leaders in this research effort. Building codes that require earthquake resistant design and construction have been implemented in Snohomish County since 1962. The standards, formulas and methods to calculate these forces have been modified and evolved as part of the normal 3-year Building Code Update and Review cycle, with significant changes in 1991. The design concept was primarily to resist stresses induced by seismic lateral forces by developing a lateral force resisting system in the structures.

The new 2003 International Building Code (IBC) identifies soils site class for most of Snohomish County as a site class D. The site classification is based on three distinct soils properties: 1) Shear wave velocity through the soils; 2) Standard penetration resistance test consistent with ASTM D 1586; and 3) Undrained shear strength, determined in accordance with ASTM D 1266 or ASTM 2850.

The ability to predict locale and strength of earthquake events has not been achieved, however on-going efforts in this area are being pursued by the scientific community. Probabilistic estimates suggest that a M9 Cascadia Subduction Zone quake is likely to occur once every 350-500 years and that M6.5-M6.8 Benioff quakes similar to those experienced in the last century occur once every 35 years. Geologists have yet to establish or satisfactorily determine the recurrence interval on the SWIF or for the Darrington-Devils Mountain faults. Best Available

Science (BAS) at this time comprises efforts to reduce the impact of seismic events by requiring analysis of site periodicity and designing structures accordingly, and by implementing the International Building Code that requires earthquake resistant construction.

Seismic Hazard Area Functions

Ground Shaking

Most earthquake damage is caused by ground shaking. The magnitude of an earthquake, distance to the earthquake focus or epicenter, type of faulting, depth (shallow or deep), and type of material are important factors in determining the extent of ground shaking or movement that might be produced at a particular site. Where there is an extensive history of earthquake activity, these parameters can often be estimated; however, in many areas of Washington they are still poorly defined.

The magnitude of an earthquake influences ground shaking in several ways. Large earthquakes usually produce ground motions with large amplitudes and long durations. In addition, large earthquakes produce strong shaking over much larger areas than do smaller earthquakes. The 1949 M7.1 Olympia earthquake produced ground shaking lasting 30 seconds and was felt over an area of 550,000 square kilometers. In contrast, the 1964 M8.3 Alaska earthquake produced ground shaking for about 300 seconds and was felt over an area more than five times larger. The November 3, 2002 earthquake near Fairbanks, Alaska registered at M7.9 and effects were noted as far away as Louisiana (USGS 2002).

The distance of a site from an earthquake affects the amplitude of ground shaking. In general, the amplitude of ground motion decreases with increasing distance from the focus of an earthquake. The considerable depth of the 1949 earthquake, 54 kilometers, put even the closest sites, those directly over the earthquake focus, at least 50 to 65 kilometers from the source of the ground shaking, a factor that contributed to the lower intensity experienced near the epicenter

The frequency content of the shaking also changes with distance. Close to the epicenter, both high (rapid) body waves and low (slower) frequency surface waves are present. Farther away, low-frequency motions are dominant, a natural consequence of wave attenuation in rock. The frequency of ground motion is an important factor in determining the severity of damage to structures and which structures are likely to be affected. At significant distance from the epicenter, structures with longer natural periods or frequencies such as high rise buildings or long span bridges are more at risk versus the single family residential or low rise commercial buildings.

Analyses of earthquake damage in Washington and elsewhere suggest that the severity of shaking depends on several factors besides the distance and magnitude of an earthquake. These factors include the kinds and thicknesses of geologic materials exposed at the surface, and the subsurface geologic structure (Rasmussen et al. 1974; Newmark and Hall 1982). Natural and artificial unconsolidated materials, such as sediments in river deltas and materials used as landfill, commonly amplify ground motions relative to motion in consolidated sediments or bedrock. Such areas, in general, have had higher levels of ground shaking in past Washington earthquakes. The thickness of unconsolidated material may also affect the amount of ground shaking produced. Certain frequencies of ground shaking may generate disproportionately large motions because of wave resonance in sedimentary basins (Rasmussen et al. 1974; Newmark and

Hall 1982). Just as the pitch of sound from an organ pipe depends on the length of the pipe and the density and compressibility of air, the various frequencies at which a sedimentary basin will resonate when shaken by seismic waves depend on the thickness, density, and stiffness of the sedimentary layers.

Subsurface structures, such as sedimentary layers that vary in thickness or degree of consolidation, may increase ground motion by focusing seismic wave energy at a particular site. The curved surfaces of buried bedrock topography may also focus waves. Langston and Lee (1983) suggested focusing as a mechanism to explain why the severity of damage observed in West Seattle during the 1965 Seattle-Tacoma earthquake seemed unrelated to surface geology in many places. The depth to bedrock changes from very near the surface in the West Seattle area to significantly deeper just a short distance away in downtown Seattle. The latest information suggests that this differential bedrock depth reflects the recently identified east-west trending Seattle Fault. However, both the work of the USGS (SHIPS) project by Brocher et al. (2000) and the work done by the University of Washington team of Dr. Derek Booth and Dr. Kathy Troost in concert with Geotechnical Consulting Engineers for the City of Seattle and King County DNR for the Brightwater Project, has brought to light the existence of a number of other smaller faults or other geologic features that previously were unknown. Two of these are located at Lowman Beach Park on Beach Drive in West Seattle and Mee Kwa Mooks Park at the foot of Jacobsen Street in West Seattle and further clarify the location of the Seattle Fault itself. Undoubtedly, this type of linear fractured crust may exist in other parts of the Puget Sound Basin as yet not fully studied by USGS.

Studies of the 1949 and 1965 Washington earthquakes have provided most of the data used to estimate future ground shaking in Washington (Langston 1981; Langston and Lee 1983; Ihnen and Hadley 1986), though data from the Nisqually Earthquake of 2001 is now being analyzed and incorporated into these estimates (Hausler and Sitar 2004). The depths of these two earthquakes (54 and 63 kilometers below Puget Sound in the subducting Juan de Fuca plate), their magnitudes, and the reports of damage at sites in Washington having a variety of geologic materials have led to estimates of future ground shaking for similar events. For example, the intensity of ground shaking in the epicentral area of a future large Puget Sound earthquake, if that earthquake occurred at a depth comparable to those of the 1949 and 1965 earthquakes, would be lower than the intensity that would be expected for a shallow earthquake of the same magnitude. The reduced intensity would be related to the effect of depth to the focus and the possible attenuation of ground shaking in some areas identified during past earthquakes caused by the nature of the geologic materials between the focus and the site.

Surface Faulting

The consequences of major fault rupture at the surface can be extreme. Buildings may be pulled apart, gas lines severed, and roads made impassable. Damage by faults is more localized than the widespread damage caused by ground shaking. Nevertheless, the identification of active surface faults is an important part of estimating future earthquake losses.

Many maps of surface faults in Washington have been published (McLucas 1980; Gower et al. 1985). Most of the faults on these maps are presently inactive, including the recently identified Seattle Fault (ICC 2003). Geologic evidence indicating active fault movement within the last 10,000 years has been reported for only a few faults in Washington. The last record for movement in the SWIF was dated between 1000-1100 years ago (Blakely 2004), but an accurate recurrence interval is still unknown. The best-documented active surface faults in the state are located near Lake Cushman in western Washington. The more recent mapping cited above has become available through the Seattle Area Geologic Mapping Project and the 1998 USGS Seismic Hazards Investigation of Puget Sound (SHIPS).

Seismicity, another indication of active faulting, has only rarely been associated with recognized surface faults in Washington. However, seismic activity has been used to define faults that do not currently rupture the surface, such as the Mount St. Helens Seismic Zone.

Subsidence and Uplift

Sudden elevation changes during earthquakes could have severe long-term economic impact on Snohomish County coastline development. The heavily urbanized and populated areas of King, Kitsap, Pierce, and Snohomish Counties, where a number of the faults are found, is home to much of the state's economic base. Scientists have gathered evidence that points to a M7 or greater earthquake on the Seattle fault about 900 A.D. Such evidence includes a seven-meter uplift of a marine terrace (Washington 2001). Submerged marshlands in several estuaries along Washington's coast suggest that episodes of sudden subsidence have occurred in the Pacific Northwest (Atwater 1987). A likely Snohomish County example of this may be found at the Thomas Eddy Park, where the forest is lying within the coastal marsh area adjacent to the Lower Snohomish River. Carbon dating indicates that many of the subsidence events at different sites in Washington occurred at the same time. For this reason, Atwater (1987) and Hull (1987) have attributed these subsidence events to the occurrence of large subduction earthquakes.

Some parts of Prince William Sound were uplifted by several meters during the 1964 Alaska earthquake. Conversely, parts of the Kenai Peninsula and Kodiak Island subsided as much as 2 meters during that earthquake (Plafker 1969). Some raised harbors on Prince William Sound could no longer be used by boats. In other areas, streets and buildings subsided so much that they were flooded at high tide. Major subsidence or uplift of large regions often occurs as a result of great subduction-style, thrust earthquakes. Such elevation changes have been reported after earthquakes in New Zealand, Japan, Chile, and southeast Alaska (Plafker 1969).

Secondary Causes of Earthquake Damage

While earthquakes may produce ground shaking, surface faulting, and vertical movements that cause direct damage to buildings and land, damage and personal injury may also be caused by several additional factors. Earthquakes may trigger ground failures such as landslides, differential compaction of soil, and liquefaction of water-saturated deposits like landfills, sandy soils, and flood plain deposits. Such ground failures may cause more damage to structures than the shaking itself. For example, after the Nisqually quake the ground gave way in an area supporting the natural gas pipeline northeast of Arlington, causing a need to structurally support or remediate the existing pipeline (Snohomish County 2001). Utilities that crossed Ebey Island within the flood plain were also endangered (City of Everett 2001).

Earthquakes may also cause destructive water waves such as tsunamis and seiches. Non-structural building components like ceiling panels, windows, and furniture can cause severe injury if shaking causes them to shift or break. Broken or impaired lifelines (gas, water, or electric lines and transportation and communication networks) can produce hazardous situations and distress to a community. After the Nisqually quake telephone and cell phone service was inconsistent as the system was overloaded with calls by the general public and first responders trying to make calls at the same time. A reservoir can be a hazard, should shaking cause a dam or a water tank to fail. One of the Arlington water tanks may be taken out of service since it does not meet current seismic standards (City of Arlington 2004).

Ground Failure

Major property damage, death, and injury have resulted from ground failures triggered by earthquakes in many parts of the world. More than $200 million in property losses and a substantial number of deaths in the 1964 Alaska earthquake were caused by earthquake-induced ground failures. A 1970 earthquake off the coast of Peru triggered an ice and rock avalanche in the Andes that killed more than 18,000 people when it buried the City of Yungay. Earthquakes in the Puget Sound region have induced ground failures responsible for substantial damage to buildings, bridges, highways, railroads, water distribution systems, and marine facilities. Ground failures induced by the 1949 Olympia earthquake occurred at scattered sites over an area of 30,000 square kilometers, and ground failures induced by the 1965 Seattle-Tacoma earthquake occurred over 20,000 square kilometers (Keefer 1983).

In reviewing records of the 1949 and 1965 Puget Sound earthquakes, Keefer (1983) noted that geologic environments in the Puget Sound region having high susceptibilities to ground failure include areas of poorly compacted artificial fill, postglacial stream, lake, or beach sediments, river deltas, and areas having slopes steeper than 35 degrees. The types of ground failures associated with past Washington earthquakes are expected to accompany future earthquakes include, soil liquefaction, and differential compaction. Such failures commonly occur in combination, for example, liquefaction may cause a landslide or accompany compaction and cause building settlement problems.

Landslides

Washington has many sites susceptible to landslides, including steep bluffs of eroded glacial deposits in the Puget Sound region and rugged terrain in the Cascade Mountains. Fourteen earthquakes, from 1872 to 1980, are known to have triggered landslides in Washington. Dozens of ancient landslides have been identified in the bluffs along Puget Sound, indicating their susceptibility to ground failure. The landslides may also be susceptible to further failure if the headwall or toe areas are steepened by erosion or excavation (Keefer 1983). Ground shaking produced by recent large Puget Sound earthquakes generated 20 landslides, some as far as 180 kilometers from the epicenter of the 1949 Olympia earthquake, and 21 landslides as far as 100 kilometers from the epicenter of the 1965 Seattle-Tacoma earthquake (Keefer 1983).

Washington's five stratovolcanos (Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helens, and Mount Adams) offer many sites for rock and ice avalanches, rock falls, and debris flows on their steep slopes. The massive 2.8-cubic-kilometer rockslide/debris avalanche on the north side of Mount St. Helens during the catastrophic eruption of May 18, 1980 was triggered by a moderate (M5) earthquake that followed 8 weeks of intense earthquake activity beneath the volcano.

The impact of landslides on stream drainages and reservoirs also can pose significant danger to populations and developments downstream (Beget 1983). Water ponded behind landslide-debris dams can cause severe floods when these natural dams are suddenly breached. Such outburst floods are most likely near volcanic centers active within the past 2 million years (Evans 1986). The Toutle River was blocked by a debris flow triggered by an earthquake during the 1980 eruption of Mount St. Helens. The debris flow dam raised the level of Spirit Lake by 60 meters. The U.S. Army Corps of Engineers constructed a tunnel through bedrock in order to lower the lake level and thereby reduce the danger of flooding from a sudden release of water and lessen the risk to persons living downstream.

Landslides or debris flows into reservoirs or lakes may displace enough water to cause severe downstream flooding (Crandell 1973; Crandell and Mullineaux 1967, 1978.) Communities and developments located downstream of reservoirs, lakes and rivers along drainages from Mount Baker, Mount Adams, Mount Rainier, Glacier Peak and Mount St. Helens must all be considered at some risk from earthquake-induced landslides.

Specifically, in Snohomish County the community of Darrington is most at risk from a lahar event and associated landslide/mudflow/flooding event from the Sauk River and Stillaguamish River system. During the February 2001 Nisqually Earthquake, a large landslide blocked the Cedar River temporarily about 5 miles upstream of Renton, Washington. The slide mass was quickly breached with equipment to avoid catastrophic flooding downstream after a slide mass failure. Other landslide prone areas like the Deer Creek landslide area on the Stillaguamish, the Lowell Larimer Bluffs, portions of Arlington Heights, Possession Lane, Picnic Point, Edmonds-Meadowdale Area, Woodway and Mukilteo bluff communities and some of the bluffs on Hat Island are more at risk locations during a seismic event (Laprade et al. 1998, WADNR 2003).

Future earthquakes in Washington are expected to generate more landslides and greater losses than reported for past earthquakes.

Liquefaction

Liquefaction occurs when very loose to loose saturated sand or silt is shaken violently enough to increase pore water pressure between individual grains effectively reducing shear strength of the soil mass. Such rearrangement has a tendency to compact the deposit. If the intragranular water cannot escape fast enough to permit compaction, the load of overlying material and structures may be temporarily transferred from the grains of sand or silt to the water, and the saturated deposit becomes “quicksand”. The liquefied material may then cause lateral-spread landslides or loss of bearing strength under foundations or roadways, depending on the depth and thickness of the liquefied zone and local topography.

If the liquefied layer is near the surface it may break through overlying “dry” deposits, forming geysers or curtains of muddy water that may leave sand blows as evidence. Retaining walls may tilt or break from the hydrostatic fluid pressure of the liquefied zone. Shallow liquefaction zones can also cause severe damage to structures whose foundation support has suddenly become fluid. Liquefaction caused basement floors to break and be pushed upward in Seattle and Puyallup during the 1949 earthquake. Other basements cracked open and completely filled with water and silt. Lighter structures may float in liquefied soil. Buried fuel tanks, if sufficiently empty, may pop to the surface, breaking connecting pipes in the process. Pilings without loads may also float upwards or sink under their own weight as they have done in the Snohomish River Delta area. Heavy structures may tilt in response to the loss of bearing strength by underlying soil. During the 1964 Niigata, Japan, earthquake, four-story apartment buildings tilted on liquefied soils, one as much as 60 degrees.

In Snohomish County a barn in the vicinity of Elm Place, Edmonds subsided into the quicksand, areas on the south side of Hat Island beach produced sand boils at the outlet to the gravel pit at low tide, and the area just north of Scriber Creek and east of Lynnwood saturated the sand unit causing instability of surface organic soils after the 1965 quake, causing horses to perish (City of Lynnwood 1976).

If a thick section of unconsolidated deposits liquefies near the surface, it will tend to flow into and fill topographic depressions. For example, a stream channel may be narrowed as saturated and liquefied deposits on both sides of the stream flow into it. Compression resulting from such flow buckled or skewed spans and damaged abutments on more than 250 bridges during the 1964 Alaska earthquake. This form of liquefaction failure was so widespread that McCulloch and Bonilla (1970) coined the term "land spreading" to distinguish it from the more widely recognized lateral-spread landslides that tend to occur on slopes due to failure along a particular subsurface layer. Land spreading may have been responsible for the disabling of three drawbridges across the Duwamish Waterway in Seattle during the 1949 earthquake. The distance between the piers in the main span of the Spokane Street bridge was shortened by 6 to 8 inches, causing the bridge to jam in the closed position until the concrete and steel edges could be trimmed off sufficiently to permit reopening.

Earthquakes may trigger a phenomenon in certain clays that produces effects similar to liquefaction in water-saturated sand. When vibrated, these "quick" or "sensitive" clays undergo a drastic loss of shear strength. For example, a relatively thin sensitive zone in the Bootlegger Cove Clay, located about 25 meters below the surface, was blamed for the spectacular lateral-spread landslides that destroyed parts of Anchorage in 1964 (Hansen 1966). The sensitive layer responsible for these landslides had been deposited in a marine environment, in contrast to the underlying and overlying fresh-water clays. Later leaching of the salt from the marine clay by fresh ground water may have increased the clay's sensitivity to vibration-induced loss of shear strength by shaking (Hansen 1966).

Differential Settlement

Structural damage commonly occurs to buildings underlain by foundation materials that have varying physical properties. Materials such as tide flat sediments, glacial outwash sands, dredging spoils, sawdust, and building rubble will settle by different amounts when shaken. These materials are prevalent under parts of the downtown and waterfront areas of Seattle, Tacoma, Olympia, Aberdeen-Hoquiam, as well as most other urbanizing neighborhoods of the last century.

Many of the areas around the local Everett logging mills within the floodplain, like Ebey Island, were filled with wood waste or sawdust. North of Scriber Lake the low peat areas were filled with Christmas trees, which caused all sorts of differential settlement havoc with the 196th Street SW road when it was straightened to connect with the new I-5 freeway on-ramps in Lynnwood (City of Lynnwood 1975).

Buildings must be constructed to accommodate for the potential of differential settlement. Examples of structures that required this type of analysis in the County include the Bon Store for Homes at the Alderwood Mall, Lynnwood, Harbor Square in Edmonds, and the Everett Homeport Facilities. Examples of roads that were evaluated for differential compaction include 128th St. SW in the vicinity of McCollum Park (landfill), Dayton Street in Edmonds, and most of the roads crossing major peat deposits, especially if the soils deposit was anticipated to remain as it has at Chase Lake and Thomas Lake (Sleight 2004).

Several water and/or gas line breaks occurred in the local cities as a result of differential compaction during the 1949 earthquake, and many buildings along the Seattle waterfront were damaged by settling during the 1965 earthquake, especially along Alki Avenue SW and within the Pioneer Square area of downtown Seattle. This was also prevalent in the Nisqually earthquake at Harbor Island and again in the Pioneer Square and SODO District of Seattle. Many waterfront areas around Puget Sound are underlain by material susceptible to differential compaction and are thus vulnerable to damage in future earthquakes (Highland 2003).

Water Waves

Tsunamis

Tsunamis are long-wavelength, long-period sea waves generated by an abrupt movement of large volumes of water (Gonzalez et al. 2002). In the open ocean, the distance between wave crests can be greater than 100 kilometers, and the wave periods can vary from 5 minutes to 1 hour. Such tsunamis travel 600 to 800 kilometers per hour, depending on water depth. Large subduction earthquakes causing vertical displacement of the sea floor and having magnitudes greater than 7.5 are the most common cause of destructive tsunamis. Large waves produced by an earthquake or a submarine landslide can overrun nearby coastal areas in a matter of minutes. Tsunamis can also travel thousands of kilometers across open ocean and cause damage and destruction on far shores hours after the earthquake that generated them.

Tsunami wave heights at sea are usually less than one meter, and the waves are not frequently noticed by people in ships. As tsunami waves approach the shallow water of the coast, their amplitude increases and wave heights increase – sometimes exceeding 20 meters. Historically, tsunamis originating in the northern Pacific and in South America have caused more damage on the West Coast of the United States than tsunamis originating in Japan and the South Pacific. The 1964 tsunami generated by the Alaska earthquake destroyed a small bridge across the Copalis River (Grays Harbor County) by hurling log debris against supporting piles. The tsunami was also detected on the Columbia River as far as 160 kilometers from the ocean. Besides causing property damage, the 1964 tsunami killed 103 people in Alaska, 4 in Oregon, and 12 in California. Newspaper accounts tell of narrow escapes along the Washington coast, but there were no fatalities. Recent work relating to analysis of coastal paleosediments in the form of sand deposits overlying shoreline and marine vegetation suggests that a large tsunami hit the Washington coast (Atwater and Moore 1992).

The regional variations in damage caused by a tsunami from a particular source region can be estimated for future earthquakes. The basis for such estimates, particularly the influence of near-shore bottom topography and irregular coastline on the height of an arriving tsunami wave, is described by Wiegel (1970) and Wilson and Torum (1972). Past tsunamis have caused only minor damage in Washington, but the potential for damage in the future is significant.

In addition to a tsunami generated by a distant earthquake, an M8 or greater subduction earthquake between the Juan de Fuca and North America plates might create a large local tsunami on the coast of Washington. Atwater (1987) and Reinhart and Bourgeois (1987) have found evidence they believe indicates that a tsunami from a nearby great subduction earthquake did affect the coast of Washington about 300 years ago. In general, local tsunamis are much more destructive than tsunamis generated from a distant source. In addition, they may occur within minutes of the earthquake or landslide that produces them, allowing little time for evacuation (Gonzalez et al. 2002). Estimates of the effect of a local tsunami in Washington are speculative because we have no written record of a large, shallow earthquake near the coast. However, the sudden submergence of coastal areas that may accompany great earthquakes might increase the amount of land in Washington susceptible to tsunami damage (Gonzalez et al. 2002).

Seiches

A seiche is a standing wave in an enclosed or partly enclosed body of water and is analogous to the sloshing of water that occurs when a bowl of water is moved back and forth. Earthquakes may induce seiches in lakes, bays, and rivers. More commonly, seiches are caused by wind-driven currents or tides. Seiches generated by the 1949 Queen Charlotte Islands earthquake were reported on Lake Union and Lake Washington in Seattle and on Commencement Bay in Tacoma, as well as north of the Tacoma Narrows Bridge.

Within Snohomish County, a small seiche was associated with the Nisqually quake at Nina Lake, which caused a subsurface landslide that took out most of the rear yard of several homes along the lake front within the subdivision (Sleight, March 2001 inspection).

Seismic Hazard Area Protection

The study of earthquakes and seismicity is a mature science, but the ability to predict location and magnitude of seismic events has not been achieved and is not imminent. Given that, the scientific literature reviewed above indicates that the impact of seismicity be mitigated to the extent possible via regulatory requirements, including preparation of site-specific seismic studies for essential public facilities and lifeline infrastructure and adherence to building codes that require earthquake resistant design and construction.

Erosion Hazard Areas

Erosion hazard areas include naturally occurring slopes, containing soils which are at high risk from water erosion according to the mapped description units of the United States Department of Agriculture Soil Conservation Service Soil Classification System. They also include marine and lake shorelines, and channel migration zones.

Excessive erosion can be very damaging to water quality in adjacent and downstream water bodies that often support salmonid fish and other species. Silt and sand-sized particles are particularly damaging to the stream environment if excessive deposition occurs. The silt and sand can bury and asphyxiate fish eggs that are deposited in gravel, can fill the spaces between gravel that support aquatic insects, and can even kill fish by damaging or clogging the gill structure. Erosion also leads to deposition of materials downstream that can create a whole host of negative impacts, including channel in-fill and avulsion, channel blockage and blockage to fish passage, burying of habitat(s), and loss of local flood storage.

Erosion Hazard Areas were originally mapped by Snohomish County in 1996 as part of the Critical Areas Regulation that is now in place. Erosion Hazard Areas were mapped based on the Soils Conservation Service mapping of highly erodible soils found in the County. In general, the finer-grained the soil, the more erosive it is. Geologists and Geotechnical Engineers on contract to the County that did the CAR soils mapping also took slope, or gradient, into account as they assessed the likelihood of excessive erosion—the steeper the slope, the more likely excessive erosion was to occur because of higher runoff energy (Urquhart 1962). As with all geologically hazardous areas, there are numerous variables at work including grain-size, soil cohesion, slope gradient, rainfall frequency and intensity, surface composition and permeability, and type of cover (e.g., pavement, pasture or forest). Erosion hazard is determined by climate, topography, soil erodibility, and land use, and is a measure of the susceptibility of an area of land to prevailing agents of erosion (Houghton and Charman 1986). Each specific land use or development activity has its own erosion hazard.

Certain areas along rivers are considered highly erodible as a result of the soils substrate and energy being imparted to the banks of the river at that particular location. When the banks erode this causes the river to migrate or the river channel to move. A slow movement or deposition of the sediment from this erosive process is referred to as accretion, whereas the sudden movement of the river by a high flood event is referred to as avulsion (West Group 1999).

Erosion Hazard Area Functions

In general, rainfall or accidental surface-water discharges begin the erosion cycle. Individual raindrops impacting a denuded surface cause soil particles of sand or silt size to break away from the surface and move downslope. As water accumulates on the surface, it tends to concentrate in small channels that develop as the soil particles are moved or "mobilized." As water accumulates in the small channels, it gains volume and energy and is able to mobilize ever-larger particles. Thus, the greater the distance over steep terrain or amount of exposed bare disturbed ground the greater the risk or likelihood of soil movement. In this way, erosion features develop on a surface—they start as very small channels, or rills, and tend to grow in size to large gullies and canyons over time. Material that is caught up in this process is carried downslope until the gradient flattens out and the energy of the soil and water mass is reduced. When the energy drops below a certain threshold, the particles, or bedload, drop out of the water. This deposition of bedload generally occurs either on land in floodplains or within waterbodies like lakes or Puget Sound or even within certain detention ponds. Very fine particles of clay minerals, once mobilized, can take days or even years to drop out of suspension in the water, depending on the radius of the particle and the specific weight of the particle in relation to the specific weight of water or the liquid the particle is falling through as well as the viscosity of this liquid. The terminal velocity of a particle dropping through a fluid can be determined by Stoke's Law.

One of the factors affecting erosion potential in a stream system is the degree of development in the basin or subbasin area. Urban developments such as parking lots, roads, single family residents, and other buildings result in the replacement of permeable natural surfaces like forest canopy and brush with impermeable surfaces. This has two effects on stormwater runoff. First, the volume of runoff tends to increase significantly, unless the natural aquifer recharge areas and wetland systems are preserved. Second, the peak rate of runoff also increases. Both effects result in a significant increase in the erosion potential within the basin or subbasin. Earlier hydraulic studies in the Swamp Creek and North Creek basins confirm this.

Climatic stresses also increase erosion potential in any given area. These stresses include simple rainfall, especially very intense storm events that drop a large volume of water over a short period of time. They also include "rain-on-snow" events wherein warm rain falls on already melting snow, similar to the event of late 1996 and early 1997 (Baum et al. 1998). This is especially true in areas with significant gradient. The warm rainfall and moderating temperatures combine with melting snow to create torrents of concentrated runoff. This occurs in both urban and rural environments and can have dramatic impact on local erosion rates over short periods of time (Terzhagi and Peck 1948).

Erosion Hazard Area Protection

It should be understood that some erosion is natural and is in fact very important to the overall function and health of a stream system. The difficulty is in determining what is the natural background level of sediment input and what exceeds it. Natural erosion and landsliding processes provide the sand, gravel, cobbles, and boulders that streams need to remain productive with respect to fish and other aquatic organisms.

Erosion Hazard Areas should be protected by promoting sound development practices including the use of Best Management Practices (BMPs) By requiring that BMPs be employed that limit erosion and sedimentation during construction, the amount of excess sediment that reaches stream systems can be limited. A Temporary Erosion and Sedimentation Control (TESC) plan should be prepared for all development activities requiring a grading permit or building permit. Appropriate BMPs and a construction sequence should be included in the TESC plan. The plan should be reviewed and approved by Snohomish County during the permitting process (Scullin 1983). BMPs that are commonly employed include covering bare ground with straw and/or plastic sheeting, using silt fences, and by planting denuded areas as soon as possible after development. Snohomish County also has advocated the use of compost mulch berms for perimeter control of turbidity and augmenting existing graded soils with a mulch topsoil to promote establishment of a good vegetated root zone (Caine 2001).

Minimizing or preventing construction on the erosion hazard areas, especially in the winter adjacent to streams and wetlands has typically been done in the County using a risk assessment analysis. Factors in this analysis include slopes, proximity to the critical area, soils type, existing vegetated cover and length of exposed surface. High hazard areas are typically not suited to grading during periods of heavy rainfall. All of these elements play a role in the adequate protection of the erosion hazard area.

Channel Migration

Areas affected by channel migration, the movement of a river or stream channel across its valley bottom, are called Channel Migration Zones (CMZs). There is no specific correlation between the extents of the CMZs and areas of flood inundation. The area within a CMZ may extend beyond the 100-year floodplain, or the 100-year floodplain may extend beyond the CMZ. Therefore, it is necessary to map CMZs as an erosion hazard area separate from the standard FEMA mandated inundation mapping.

Channel migration is the process of a river channel moving across or within its valley bottom. Channel migration occurs over variable timeframes, ranging from the gradual lateral progression of meander bends to the abrupt shifting of a channel to a new location. In general terms, a CMZ is a corridor of variable width that includes the current river channel plus the adjacent area through which the channel has migrated or is likely to migrate within a given timeframe. Within the CMZ corridor, water, sediment, and organic material are moved by fluxes between river and floodplain and are routed from headwaters to mouth on time scales of days to centuries.

A basin-scale perspective of channel migration provides an initial overview. Drainage basins can be broken into three zones in the downstream direction: the rugged headwaters dominated by erosion and sediment production; a middle zone of sediment transport; and a downstream zone of deposition (Schumm 1977). These three subdivisions of the fluvial system may seem like a simplification, because sediment is eroded, transported, and deposited in all three zones

(Schumm 1977). These three zones are similar to the source, transport, and response segments of a watershed described by Montgomery and Buffington (1993), with channel changes such as channel migration most commonly occurring in the generally downstream response segments where areas of sediment deposition predominate (Montgomery and Buffington 1993).

Channels in the steeper erosion and sediment production zone and areas dominated by sediment transport may not show significant channel migration over time scales of a few decades. Areas of deposition, especially the transition from a transport to a depositional zone, would be areas of likely channel migration (Church 1983; Montgomery and Buffington 1993). These conditions exist where channel gradient and confinement decreases markedly, such as where a steeper river emerges from foothills onto a broad, flat floodplain. In the major Snohomish County rivers, most of which flow from headwaters in the Cascades to mouths at or near sea level, the segments with a history of channel migration typically are located in just such depositional areas.

The footprint of a channel can be expressed as a percent of the total floodplain area in plan view. As the channel migrates, the composite footprint of its sequential locations will occupy an increasing percentage of the floodplain. By extension, the timeframe needed for a channel to migrate and occupy its entire floodplain can be calculated as a “floodplain turnover rate” (O’Connor et al. 2003), which might be on the order of hundreds to thousands of years in an alluvial channel of western Washington. Given time and without obstruction, a natural, unimpeded, meandering channel can swing and shift across its valley and the entire pattern may sweep downstream, resulting in a complete reworking of the alluvial floodplain (Schumm 1977).

Hence, the generally flat floor of a valley, the alluvial floodplain, was constructed by the river during lateral channel migration and by deposition of sediment. In alluvial floodplains, the river has occupied or migrated through every position of the valley floor at some point in the past (Dunne and Leopold 1978). The river channel moves laterally by erosion of one bank and simultaneous deposition on the other. As a channel migrates, there may be physical features evident in the floodplain such as progressive erosion and deposition at meander bends. Other features, such as side channels or oxbow lakes (crescent-shaped body of standing water situated in an abandoned meander) may be evidence that a channel has moved by shifting abruptly or by cutting off a meander bend. Though such field conditions provide evidence of channel migration, the actual boundary of the CMZ may not be readily evident in the field because the lateral extent of the CMZ typically depends on selection of a timeframe within which migration occurs (as described further below).

Types of Channel Movement

Channel movement can occur in both vertical and horizontal directions to produce channel migration. Vertical channel movement occurs as either a raising or lowering of the channel bed. Increases in channel bed elevation result from sediment deposition and aggradation. Significant increases in bed elevation allow a given flood flow to gain greater access to side channels and overbank areas, or increase exposure to erodible banks, all of which increase the likelihood of horizontal channel movement. Decreases in channel bed elevation result from channel incision, local or general channel scour, and degradation. Significant decreases in bed elevation lead to bank collapse and channel widening (Rapp and Abbe 2003).

Horizontal channel movement includes lateral channel migration, avulsions, channel widening and channel narrowing, and involves erosion of the existing floodplain and terraces (Rapp and Abbe 2003).

Lateral channel migration results from erosion of floodplain material along one bank concurrent with deposition of sediment along the other bank. Bank erosion is the primary channel process necessary for channel migration to occur (Leopold et al. 1964). Ongoing lateral channel migration typically results in development of meander bends, which themselves may migrate in a downstream direction. Rivers tend to establish secondary circulation patterns of flow that moves downstream in a generally spiraling motion, where a descending flow pattern encourages scour and an ascending flow direction favors deposition. The scour and deposition from secondary circulation is associated with development of bed forms such as pools and riffles. As pools alternate from one side of the channel to the other, they scour and undermine the outside banks, initiating meander development (Knighton 1998). If the processes of erosion and deposition are in rough equilibrium, there may be little net change in a cross sectional area even as the channel meanders or migrates across the floodplain (Dunne and Leopold 1978).

An avulsion is an abrupt shift of the channel to a new location, often with little erosion of the land between the old and new channel locations. An avulsion can happen during a single flood event, for instance, if a mainstem river is obstructed by a woody debris jam and reroutes the river into a side channel during high flows. Another type of avulsion is the neck cut-off of a meander bend, which can occur as a meander bend increases in sinuosity until parts of the meander loop connect and bypass the longer, circuitous path of the entire meander. Chute cutoffs cut across a point bar and may occur more commonly than a neck cutoff (Rapp and Abbe 2003). Conditions that would favor the occurrence of avulsion include the existence of side channels accessible to frequent flows, or the ongoing development of sinuous meander bends.

Channel widening and channel narrowing result in horizontal changes to the channel dimensions, although channel alignment may not change. Channel widening might occur with channel aggradation and/or channel braiding. Channel narrowing can result as a response to upstream decreases in sediment or water discharge.

Channel movement is difficult to predict with certainty on alluvial fans (WA DNR 2001). An alluvial fan is a fan-shaped feature composed of streamflow and/or debris flow sediments deposited usually at a topographic break such as the base of a mountain or a valley floor at the outlet of a steeper tributary. The alluvial fan is formed as the tributary deposits sediment to the point where its channel elevation is higher than the adjacent fan; the channel then shifts location to flow to the adjacent, lower elevation. As this ongoing process continues, the channel shifts to deposit sediment in an arc radiating from the tributary outlet. A braided channel or channel network is common on an alluvial fan. By its inherent tendency to shift channel locations, and resultant uncertainty in predicting channel migration, the entire surface of the alluvial fan is considered a channel migration zone of its source tributary (WA DNR 2001).

Some Natural Factors that Influence Channel Migration

Lateral channel migration meets a solid boundary in bedrock. In areas where the river channel is in direct contact with bedrock, bank erosion is assumed to be minimal over scales and timeframes typically used in channel migration studies (Rapp and Abbe 2003).

Channels confined by narrow valleys are less likely to move laterally and so may have little or no channel migration zone. The degree of channel confinement can be expressed as a ratio of valley floor width to channel width, where a ratio of less than 2:1 indicates high confinement and lack of a CMZ (WA DNR 2001). A CMZ also is interpreted to not exist where there is a consistent lack of evidence of channel movement in the historic record, in current aerial photos, and in field observations (NMFS 2000).

A valley wall may appear to be the boundary of a CMZ as the de facto edge of a floodplain, but the greater elevation of a valley wall does not preclude channel migration. An eroding vertical bank of unconsolidated material such as a terrace of older alluvium or glacial deposits does not prevent toe erosion, transport of sediments, and lateral channel migration (Rapp and Abbe 2003). Lateral channel migration into such terraces or unconsolidated bluffs may proceed at a slower rate than through younger floodplain alluvium (Shannon and Wilson 1991).

The susceptibility of riverbanks to slope instability and mass failure depends on their geometry, structure, and material properties (Knighton 1998). Undercutting the toe of tall, steep slopes by the river decreases slope stability and can result in landslides directly into the channel, particularly in geologic units predisposed to landsliding. At that point, hillslope delivery of sediment and fluvial sediment transport may become coupled in a “pseudo-cyclic process” of basal erosion, upper bank failure, lower bank accumulation, and removal of failed material by river transport (Knighton 1998). The river’s flow may erode and remove relatively small deposits, but a landslide mass that blocks the channel and is not eroded will reroute the channel as an avulsion.

Slope failure by landslide or mass wasting introduces both sediment and woody debris to the channel. Other input sources of woody debris to the channel include wind throw, bank erosion, and fluvial transport from upstream, in both chronic and episodic time scales (Bilby and Bisson 1998). Leaching, fragmentation, decay, consumption by invertebrates, and fluvial transport all contribute to the export of wood from a channel (Keller and Swanson 1979). Studies that reconstruct historic channel conditions document prodigious amounts of woody debris in mainstem channels of the Pacific Northwest and Puget Sound lowlands (Maser and Sedell 1994; Collins et al. 2003).

Present-day accumulation of large woody debris (LWD) as stable, in-channel structures can influence channel hydraulics, channel morphology, sediment accumulation, channel migration, and riparian forest development morphology at the sub-reach and reach scale (Abbe and Montgomery 2003; O’Connor et al. 2003; Collins and Montgomery 2002; Bilby and Bisson 1998; Abbe and Montgomery 1996). Stable LWD structures can resist channel migration, forming a revetment that halts local bank erosion, often altering the orientation of flow relative to the jam. Stable LWD jams that persist long enough to be buried in a floodplain are associated with anomalous forest patches older than the surrounding floodplain forest (Abbe and Montgomery 1996), indicating long-term resistance to lateral erosion. The type of debris jam and the presence, number, size, stability, and orientation of the key pieces of LWD will determine the stability of the jam and the effect of the jam on channel stability (Abbe and Montgomery 2003; Abbe and Montgomery 1996).

The effects of LWD accumulations on channel stability can increase or decrease bank stability depending on the specific setting (Keller and Swanson 1979). Bank erosion and channel shifting that entrain floodplain sediment and LWD can promote channel movement and instability by diverting flows that in turn causes further bank erosion and entrainment of sediment and wood. Woody debris jams in low gradient meandering channels of moderate size may facilitate formation of meander cutoffs, increase channel width, produce mid-channel bars, and affect channel morphology (Keller and Swanson 1979). LWD can be a primary determinant on channel form in small streams; wood has less of an effect on channel form in larger streams (Bilby and Ward 1989; Bilby and Bisson 1998).

Woody debris accumulations appear integral to formation and maintenance of an anastomosing (i.e., branching and recombining) channel pattern (Abbe and Montgomery 2003) and to causing avulsions, maintaining multiple-channel morphology, and regulating flow from main channels into perennially flowing floodplain sloughs (Collins and Montgomery 2002). Wood jams are often the mechanism that triggers a channel to avulse or switch flow from one channel to another (Collins and Montgomery 2002; Collins et al. 2003). May (2002) states that channels with abundant accumulation of in-channel LWD often have more active channel migration.

Accumulation of LWD induces upstream deposition of sediment and thereby can raise the elevation of the channel bottom and water surface for channel distances on the order of 1-10 channel widths (Abbe and Montgomery 2003). Increases in channel bottom and water surface elevations in turn allow flows into previously inaccessible side channels and thereby increase the likelihood of horizontal channel movement, as described in the ***Types of channel movement*** section above.

Mapping Channel Change

A common starting point for mapping channel movement and delineating CMZs is a compilation of archival records to document change in location from historic to contemporary channels. The floodplain turnover rates and channel and floodplain dynamics described earlier were calculated for the Quinault and Queets Rivers by comparison of up to nine sets of channel locations dating from 1900 to the present (O'Connor et al. 2003). Methods in development in the Puget Sound area characterize historical river landscapes and aquatic habitat using a geographic information system (GIS) as well as modern topographic information, aerial photography, and field studies (Collins et al. 2003).

Ham and Church (2000) mapped channel features for five dates between 1952 and 1991, using GIS to analyze changes in erosion and deposition volumes and relate those volumetric changes to riverbed material transport via a sediment budget approach. While the focus of Ham and Church (2000) was on sediment volumes, their characterization of plan-form changes in channel conditions through time used the same methods and tools employed in a channel migration analysis. Graf (1984) measured the change in channel locations through time with a grid framework of cells superimposed on the floodplain to calculate the probability that any given floodplain cell will be eroded. Comparison of channels over a number of time intervals from 1871 to 1978 showed that the probability of a cell being eroded within a given period of time is directly proportional to the sizes of the annual floods during the period and inversely proportional to the distance upstream and the distance lateral to the channel (Graf 1984).

These studies and others suggest that at least 50 years of remote sensing data such as aerial photos (at intervals of five to 10 years) are necessary to reveal meaningful trends in channel change and bed material transport rates (Rapp and Abbe 2003).

CMZ Definition and Delineation

There are few examples from scientific literature that define CMZs with specificity. No studies were found that identify various CMZ definitions and evaluate the adequacy of resulting CMZ delineation in protecting the affected area from channel migration hazard. References that address CMZ definitions and delineation are described here.

"Definitions that can be used to unquestionably identify exact undisputed boundaries of stream corridors or riparian areas or channel migration zones are hard to come by. Clear identification of boundaries is difficult because streams and riparian areas are not fixed in time and space" (Bolton and Shellberg 2001). Because stream channels are naturally areas of disturbance, floods, droughts, fires, and landslides can all affect the location of the wetted stream channel and adjacent riparian areas over time (Naiman et al. 1992). A time period needs to be specified when defining a channel migration zone or area through which a channel is expected to move. The extent of channel migration will vary depending on the time frame of interest (Bolton and Shellberg 2001). Delineation of a CMZ boundary identifies the area in which channel processes will occur during the selected period of time; the CMZ boundary is stationary for the design life of that CMZ delineation (Rapp and Abbe 2003).

A period of 100 years often is identified as an appropriate timeframe (Bolton and Shellberg 2001). Reasons for using this timeframe may include that the 100-year floodplain is mapped to identify flood hazard due to inundation, or it may be because CMZ mapping relies on assembly of archival material and the record of relevant information often dates back about 100 years (NMFS 2000). There is evidence that 100 years provides sufficient time for the growth of a tree to the height that it would be functional LWD were it to fall into the channel (NMFS 2000), which indicates a scientific basis for selecting the 100-year time period. However, most CMZ definitions that incorporate a time period do not indicate a scientific basis. For example, FEMA (1999) states that "there is no apparent scientific basis to choose 60 years" as the time period used to define erosion hazard areas in the National Flood Insurance Reform Act of 1994. The same could be said about selection of any specific time period for a CMZ definition (unless it is tied to a physical process of specific duration): it is more of a policy decision than science-based determination.

Pollack and Kennard (1999, in Bolton and Shellberg 2001) defined the channel migration zone as the area that the stream and/or its side channels could potentially occupy under existing climatic conditions. If "existing climatic conditions" were to include the period since the last glaciation, then the CMZ would likely encompass the entire valley bottom, along with lower terraces and hillslopes adjacent to the floodplain where the stream is likely to meander. Such a CMZ definition, based on a geologic timeframe, would be consistent with Schumm's (1977) 'sweeping channel' definition and the 'river constructing its full alluvial floodplain' per Dunne and Leopold (1978).

Skidmore et al. (1999) mapped four different boundaries of the lateral extent of likely channel movement along a seven-mile stretch of the Nooksack River using the following four criteria: 1) a corridor based on meander amplitude; 2) a composite of historic channel locations; 3) the area within geologic controls such as alluvial terraces features and geologically defined valley margins; and 4) the 100-year floodplain. The outer edge of channel movement under these four mapping approaches could each be taken to be a CMZ boundary. The four CMZ boundaries were largely coincident along one bank defined by geologic controls. There was no consistent trend in the CMZ boundaries along the other bank except that the 100-year floodplain was generally the widest. Skidmore et al. (1999) concluded that channel migration corridors are best delineated from a combination of methods.

FEMA (1999) reviewed a dozen case studies nationwide to evaluate the feasibility of mapping riverine erosion hazard areas (REHAs). Five of the 12 case studies (including King County) resulted in an erosion hazard area delineation that is presently used to regulate land use in REHAs. FEMA concluded that it is technologically feasible to conduct riverine erosion studies and establish conclusions regarding the likelihood of future erosion (FEMA 1999).

CMZs were mapped along parts of four rivers in King County (Shannon and Wilson 1991; Perkins 1993; Perkins 1996) using a combination of historic studies and field investigation. A compilation of historic channel locations is prepared, from which representative historic channel migration patterns and rates are characterized. The potential for avulsions is identified from maps and aerial photos and verified in the field. An unconstrained probable outer limit of future channel migration is predicted based on representative historic channel migration patterns and rates, potential avulsion sites, meander amplitudes, and the width of the historic meander belt. Relative levels of channel migration hazard are mapped as severe hazard areas, based on 100 years of predicted channel migration, and moderate hazard areas, which is the area between the severe hazard area and the predicted outer boundary of future channel migration. Lastly, constructed features such as infrastructure, levees, and revetments that pose legitimate constraints to channel migration are taken into account and the CMZ boundaries are modified accordingly (Perkins 1993, 1996).

CMZs were mapped along parts of three rivers in Pierce County (GeoEngineers 2003). The CMZ is delineated based on several factors, including the river's Historic Channel Occupation Tract (HCOT) over the observable period of record, its unconstrained character and rate of channel migration, and the locations of ancient and historic abandoned channels. The CMZ is delineated as the area through which lateral migration would proceed over 25 years landward in each direction from the edge of the HCOT, assuming that levees and revetments do not constrain channel migration. To recognize relative hazard within the CMZ, three Migration Potential Areas (MPAs) are also delineated. The severe MPA includes the HCOT plus the area through which the river could travel in five years of steady lateral migration. The moderate MPA is generally the HCOT plus 15 years of channel migration. The low MPA is the area landward of the moderate MPA to the outer boundary of the CMZ (GeoEngineers 2003).

Rapp and Abbe (2003) define the CMZ as the geographic area where a stream or river has been and will be susceptible to channel erosion and/or channel occupation during a specified period of time. The CMZ is the sum of several different components of the river landscape, some which may not apply in every CMZ study. The following illustrates the variables present in the CMZ delineation equation:

CMZ = HMZ + AHZ + EHA – DMA

HMZ = historical migration zone (the collective area the channel occupied in the historical record)

AHZ = avulsion hazard zone (the area not included in the HMZ that is at risk of avulsion over the design life of the CMZ)

EHA = erosion hazard area (the area not included in the HMZ or the AHZ that is at risk of bank erosion from stream flow or mass wasting over the design life of the CMZ)

The EHA has two components:

EHA = GS + ES

ES = erosion setback (the area at risk of future bank erosion by stream flow)

GS = geotechnical setback (channel and terrace banks that are at risk of mass wasting, due to erosion of the toe. The GS projects from the ES at a side slope angle that forms a stable bank configuration, thereby accounting for mass wasting processes that will promote a stable angle of repose

DMA = disconnected migration area (the portion of the CMZ where man-made structures physically eliminate channel migration).

Landslide Hazard Areas

Landslide Hazard Areas have long been recognized in the Puget Sound Basin and have been studied in depth by the academic community, government scientists, and the regional consulting engineering community (ASCE and AEG Geotechnical Annual Seminars 1985, 1991 and 1998, Gerstel 1996). This regional information is in addition to a large body of knowledge about landslides that has been developed worldwide. The mechanics of landsliding processes are well understood, though the site-specific elements of each event, occurring as they do in natural materials and natural settings, are highly variable. Gaps in current knowledge of the technical aspects of landsliding and slope failure are relatively minor and are related to that inherent variability rather than to ignorance of more fundamental elements of these processes (GeoEngineers 1995). It should also be noted that because of the variability associated with landslide hazards, evaluation of these areas is subject to some level of uncertainty. The uncertainty is generated by limited subsurface information and subtle changes in soil properties, structures, and groundwater elevations that can have significant impact on stability models.

Landslide Hazard Areas are areas of the landscape that are at high risk of future soil movement or slope failure or that presently exhibit downslope movement of soil and/or rocks and that are separated from the underlying stationary part of the slope by a definite plane of separation or geologic contact (Landslides and Engineering Practice Highway Research Board 1958). That plane of separation or geologic contact may be very thin or very thick and may be composed of multiple failure zones depending on local conditions, including soil type, slope gradient and groundwater regime. Sliding includes slow, long-term, and plastic deformation of slopes that occurs within a system of sliding planes.

Many of the local Counties' and Cities' major valleys and shoreline bluffs are underlain by steeply sloping glacial deposits that are highly susceptible to landslides (Palmer 1998). These unstable slopes can be very hazardous to people and structures. The identification of areas that are susceptible to landsliding is necessary to provide guidance when designing and siting or constructing structures or clearing and grading on these steep slopes. A great deal of local information was collected and mapped by University of Washington, the local geotechnical community, and United States Geological Survey personnel, especially most recently in the southwestern portion of the County tied to the KCDNR Brightwater project and the City of

Seattle Landslide Mapping project (KCDNR, Brightwater EIS, 2003; Lambrechts 2002; Robinson et al. 1991)

The surficial geology of the Puget Lowland consists mainly of Pleistocene glacial, alluvial, and marine sediments; little bedrock is exposed. Major Quaternary stratigraphic units exposed in coastal bluffs overlooking Puget Sound include nonglacial sand, silt, and clay, which are overlain by a sequence of glacial deposits, primarily the Vashon Drift (Mullineaux et al.1965). The basal member of the Vashon Drift is a widespread deposit of dense glacial clay and silt, called the Lawton Clay Member (Tubbs 1974a). A deposit of sand, known as the Esperance Sand Member, overlies the Lawton Clay Member. For convenience we will refer to these units as the Lawton Clay and the Esperance Sand. The basal contact of the sand is transitional over a few tens of meters, where layers of sand and clay are interbedded. Within this transitional zone, individual strata are laterally discontinuous. The Esperance Sand becomes pebbly near the top and grades into the Vashon Drift advance outwash. The Vashon Till, which is generally compact and hard, overlies the advance outwash or the Esperance Sand. The majority of landslides that have been extensively studied occurred in these glacial sediments, including outwash, till, Esperance Sand, and Lawton Clay (Thorsen 1989, Tubbs 1974a). Landslides also occur in postglacial colluvial deposits derived from the glacial sediments and in unconsolidated fill placed by humans.

Landslides have been a significant problem in Snohomish County for many years, and several landslides occur every year during the rainy season, generally from November through April, (Thorsen 1989). Storms have triggered significant numbers of landslides in 1972, 1986, 1990, 1996, 1997 and 2003 (Tubbs 1974a, b; Laprade1986; Miller 1991; Evans 1994; Gerstel 1996; Harp et al.1976). Tubbs (1974) reported on 1972 storm-induced landslides in the City of Seattle and noted that many of the landslides occurred in or near the transitional zone between the Esperance Sand and the underlying Lawton Clay. Thorsen (1987, 1989) attributed most landslides in the Puget Lowland to excess ground water, while Gerstel (1996) concluded that both seepage of perched ground water and infiltration of surface water contributes to instability of thin colluvium and fill overlying glacial materials.

Efforts to reduce landslide-related losses have been ongoing for at least 20 years. Relative-slope-stability maps at several scales were developed in the 1970s for many of the urbanized areas surrounding Puget Sound (Miller 1973; Artim 1976; Smith 1976; Laprade 1989). Despite these efforts, losses continue to mount because; (1) economic growth continues to exert pressure to develop in or near landslide-prone areas, such as view bluff property; (2) increased erosion and consequent downcutting caused by urban runoff has locally reduced slope stability (Booth 1989); and (3) new or previously unidentified landslides damage structures that were built in unstable areas before critical area regulations existed.

Landslide Hazard Area Functions

Sliding phenomena involve such a wide variety of processes and contributing factors that classification becomes a very complex problem. Many classification systems have been proposed over the years, but for purposes of simplicity, the following types of landslides have been identified for discussion (Laprade 1998). These landslide types are as follows: (1) Rapid Shallow; (2) Block Fall; and (3) Deep-Seated. In very general terms, a landslide is movement downslope of a mass of soil, rock, or both and (nearly always) saturated with water. The downslope movement may be very swift or may be very slow depending on the type of material involved, groundwater regime and condition, slope gradient, and a host of other variables. The mass of material that is mobilized may be shallow or surficial in nature, rapidly moving and very small to very large in scale – (Type 1), or it may extend very deep underground (deep-seated,) slow moving, and huge in size (Type 3) or it may be a combination of these. Oftentimes, landslides are a "nested" series of failure planes that back-rotate against one another as the failure occurs resulting in a series of failure blocks or "benches" on the surface of the slide. In addition, very steeply sloping areas like bluffs above local rivers and Puget Sound may fail as large falling blocks of material (Type 2). Debris Flows comprise a fourth type of slope failure and are oftentimes caused by or sourced by (Type 1) shallow landslides or mudslides. These flows can move with great rapidity and are often responsible for blocked roads and slight to severe structural damage.

As described above, landslides in Snohomish County occur in sloping areas that are underlain by interbedded sediments that vary in grain size. For instance, a typical landslide along the Puget Sound bluffs will occur in the Esperance Sand Member or Unit that is deposited over the relatively impermeable Lawton Clay Member or Unit. Water from precipitation percolates down through the more permeable sands and silty sands until it hits the silt/silty clay layer. The water then flows laterally along the upper surface of the impermeable layer until it reaches the slope face or "daylights." Oftentimes the water cannot move as fast laterally as it is being deposited by precipitation from above and the water builds up and saturates the sand layer. As the water builds up, pore water pressure increases between the individual soil particles, and the soil mass as a whole begins to lose shear strength. At some point, the loss of shear strength allows particles that were formerly "locked" together to start sliding past one another under the influence of gravity.

Depending on a variety of factors including the gradient or "dip" of the soil layers, the amount of water and rate of accumulation and the type of material involved, the rate of movement may be very slow (creep) or very fast. In either case, the soil mass can and does cause catastrophic damage to structures that lies above it or that lies in its path. Landslides that move relatively swiftly may strike structures before they can be evacuated, and injuries or fatalities can and do occur. Landslides can also be triggered when there is a loss of lateral support at the bottom, or toe, of a slope due to the action of water, either in a stream or river or because of wave action in bluff settings. As the toe is eaten away, support for the overlying soil mass deteriorates and eventually gravity causes the slope to collapse. This often occurs as a block fall type of slope failure and is very rapid once initiated and for that reason can be extremely hazardous (Thorsen 1989).

Removal of vegetation either through development or urban forest practices can have a dramatic affect on the stability of slopes (Booth 1989). Denudation results in rapid runoff and saturation of surficial soils that consistently lead to failures. Vegetation and its organic duff layer on the earth's surface reduce the energy of rain splash and greatly reduce erosion. The duff layer effectively stores water from rainfall and snowmelt over the short term and slows down infiltration into the underlying soil mantle. Vegetation removes water from the soil matrix through its roots and stores it in the body of the plant. Water that is taken up into the plant is eventually released back into the atmosphere through the process of evapotranspiration. These processes enhance stability of slopes by reducing the volume of water in the underlying soil mantle. Undisturbed stands of mature trees can have a dramatic effect on the infiltration of water into the soil. For instance, an individual mature Loblolly Pine tree (a California species which has been extensively studied for this purpose) can remove upwards of 100 gallons of water from the soil mantle over a 24 hour period via evapotranspiration. It is believed that large conifers found in the Northwest approach that water uptake (Abbe and Montgomery 1996).

The effect of the vegetative root mass on slope stability has been studied for some time, by a number of different investigators, particularly by Donald Gray and Tuncer Edil at the University of Wisconsin at Madison. Depending on species, plant density, and slope geometry, the tensile strength that is imparted to the soil matrix by the root mass can be enormous. Removal or death of the plants and rotting of the root mass rapidly reduces this tensile strength and can destabilize an otherwise stable or marginally stable slope (Gray and Meghan 1981)

Large woody debris (LWD) is a term that describes large pieces of wood that have been naturally deposited in aquatic areas like streams, wetlands, and marine beaches through a process called recruitment. Recruitment occurs via deadfall, storms, and landslides. LWD is very important to the natural function and health of aquatic areas. It provides nutrients to the aquatic area, provides shelter from predators to fish and amphibians, provides some shade, and serves to stabilize stream channels and beach environments (Abbe and Montgomery 1996). LWD can also be placed by natural resource managers in an effort to improve salmon habitat.

Large amounts of LWD are deposited as unstable forested slopes fail. A large “slug” of LWD input, which occurs during a landslide in a forested area, is retained in the aquatic area, particularly in stream systems, at a very high rate due to bulking of the LWD in the stream channel (Booth 1989). The impact to turbidity on streams and rivers systems is as great from natural landslides as from development activity. A downside to the LWD recruitment that occurs historically in Snohomish County has been in the accumulation of LWD on bridge abutments or adjacent to structures during flood events.

Landslide Hazard Area Protections

Literature indicates that buffers should be established around the perimeter of mapped landslide hazard areas (Gerstel et al. 1997). More specifically, buffers should be established from the tops and toes of steep slopes. Alderwood-Everett soil types make up approximately 37 percent of the land area of the SCS Surveyed Soils within Snohomish County. Historic performance specific to this Snohomish County soil type indicates that slopes of less than about 33 percent are relatively stable – the “slippage potential is moderate.” Slopes greater than about 33 percent are significantly less stable and their “slippage potential is severe” (Dubose 1983) and IBC requirements dictate a ‘bluff height divided by 3’ setback for top of banks not to exceed a 40-foot setback for footings and a ‘bluff height divided by 2’ not to exceed a 15-foot setback for toe of slopes. The building official is provided latitude to request for a professionally prepared geotechnical report or soils investigation if alternate footing setbacks from banks or bluffs are contemplated. Development that is proposed within those setbacks or within the slide area itself should meet scientifically based rigorous design and construction standards. Because of the extreme variability that is exhibited by areas that are subject to landsliding, site-specific studies may be required in order to design, construct, and safely occupy a structure that is to be built in or adjacent to a landslide area. The hazard area and proposed development should be evaluated by a geotechnical engineer or engineering geologist, including subsurface exploration in the area, soil sampling and testing, and development of a detailed construction sequencing and monitoring plan and slope failure analysis. The County may request that an independent geotechnical evaluation be performed if there appears to be a question of safety.

Volcanic Hazard Areas

Volcanic Hazards comprise a variety of phenomena that occur in zones around an active volcano. In the Pacific Northwest, the presence of a series of subduction zones and stratovolcanos presents a unique and very dangerous hazard to local populations and infrastructure. Volcanoes of this type, like Mount St. Helens and Mount Rainier, erupt in a very violent fashion and deposit enormous amounts of material onto the landscape. These deposits occur in a number of different ways, all of which pose hazards to humans and the environment. As with Seismic Hazard Areas, which are only hazardous during and immediately after an earthquake, these areas generally only pose hazards during and immediately after eruptions of the local volcano. Because eruptions occur very infrequently, it is easy to minimize the dangers associated with a volcano like Glacier Peak.

Tilling and Lipman (1993) estimated that worldwide, 500 million people will be at risk from volcanic hazards by the year 2004. In the past 500 years, over 200,000 people have lost their lives due to volcanic eruptions (Tilling 1980). An average of 845 people died each year between 1900 and 1986 from volcanic hazards. The number of deaths for these years is far greater than the number of deaths for previous centuries (Tilling 1991). The reason behind this increase is not due to increased volcanism, but rather to an increase in the amount of people populating the flanks of active volcanoes and valley areas near those volcanoes (Tilling 1991). As population in Snohomish County increases, encroachment into areas that may be subject to volcanic hazards increases. Regulatory restraints or sensible siting of homes adjacent to potential lahar areas may help save lives during the next eruption on Glacier Peak.

In recent years, with the eruptions of Mount St. Helens and Mount Pinatubo, many advances have been made in the study of volcanoes, particularly in eruption prediction. Difficulties arise because though there may be similarities between volcanoes, every volcano behaves differently and has its own set of hazards. That is why it’s important for geologists, volcanologists, and geophysicists to study and monitor volcanoes

Mapped volcanic deposits and satellites are utilized to evaluate volcanic features, ash clouds, melting ice caps, melting glaciers, and gas emissions. Hazard maps are produced using these data as well as monitoring data from seismic activity, ground deformation, geomagnetism, gravimetrics, volcanic gases, flow rates, sediment transport, water level of area streams and lakes, and geoelectrical and geothermal changes. Hazard maps indicate the types of hazards that can be expected in a given area during or immediately prior to the next eruption. Dating of these volcanic deposits helps determine how often an eruption may occur and the probability of an eruption each year. Monitoring of a volcano over long periods of time will indicate changes in the volcano before it erupts. These changes can help in predicting when an eruption may occur.

Volcanic Hazard Area Functions

In Snohomish County, widespread damage from a volcano is most likely to come from an eruption on Glacier Peak. It is less likely, though possible, that damage from ashfall and acidic aerosols could result from an eruption on one of the other subduction zone volcanoes found along the West Coast of the United States (Wolfe and Pierson 1995). In general, the major hazardous geological processes associated with the eruption of a volcano like Glacier Peak are as follows.

Tephra Fall

During explosive eruptions, a mixture of hot volcanic gases and tephra, fragments of volcanic rock and lava, including volcanic ash, is ejected rapidly into the air from volcanic vents. The finer fraction of the tephra is commonly less dense than the air and rises into the air until no longer buoyant – in the case of the 1980 eruption of Mount St. Helens, the ash column rose about 25 km in less than 30 minutes. As the energy to keep them suspended diminishes, the particles begin to fall under the influence of gravity. Larger particles fall out first and nearer the volcano while sand-sized and finer particles may fall out many hundreds of kms away. The tephra forms a blanket-like deposit that is thicker near the volcano and thinner and finer with increasing distance from the vent. (Wolfe and Pierson 1995). At Glacier Peak, the best example of this is at Cinder Cone on the west side of Glacier Peak north of Red Pass within Snohomish County.

The major hazards associated with tephra fall are: (1) impact of falling fragments; (2) suspension of abrasive fine particles in the air and water; and (3) burial of structures, lifelines, and vegetation. As learned in the 1980 eruptions of Mount St. Helens, tephra fall can cause severe social disruption over a vast area.

Fragments larger than a few centimeters (1 to 2 in), that have sufficient mass to cause severe injury or damage through impact, generally fall within about 10 km (6 mi.) of the vent. Thus, damaging or lethal impact from falling tephra is likely only in the immediate vicinity of a stratovolcano (Wolfe and Pierson 1995).

Ash suspended in the air from a large eruption can be a major source of aggravation and hazard even hundreds of kilometers (a few hundred miles) downwind from its source, both during its initial accumulation and later as fine dry ash is remobilized by wind or passing vehicles. Airborne ash (a) causes eye and respiratory irritation for some people and can cause severe air-quality problems at critical facilities such as hospitals; (b) can cause severe visibility reduction, even complete darkness during daylight hours, which can make driving particularly hazardous; (c) can damage unprotected machinery, especially internal-combustion engines; (d) can cause short circuits in electric-power transmission lines; and (e) can endanger aircraft flying through ash clouds, especially jet aircraft, which can completely lose engine power. Suspension of ash in water can lead to damage at hydroelectric facilities, irrigation pumping stations, sewage-treatment facilities, and stormwater systems.

Burial by tephra can collapse roofs of buildings and other structures, break power and telephone lines, and damage or kill vegetation. Wet tephra is 2 to 3 times heavier than dry uncompacted tephra and adheres better to sloping surfaces. Ten centimeters (4 inches) of wet tephra impose a load in the range of 100 to 125 kg/ m2 (approximately 20 to 25 lb/ft2), sufficient to cause some roofs to collapse (Wolfe and Pierson 1995).

Before 1980, the hazard from tephra fall was generally considered smaller than from other volcanic phenomena, and was commonly ignored in planning responses to volcanic crises. Yet, the 1980 eruption of Mount St. Helens showed that even thin tephra accumulations can disrupt social and economic activity over broad regions. Ash can cause or exacerbate pulmonary problems in people and animals. Even thin tephra accumulations may ruin crops. Tephra can contaminate surface water, plug storm sewer and even sanitary sewer systems, and obstruct highways and irrigation canals. Airports and highways can be closed for days. Near the volcano, clouds of falling tephra are commonly accompanied by lightning (Waitt et al. 1995).

Pyroclastic Flows

Pyroclastic flows are avalanches of hot (300 to 800°C,) dry, volcanic rock fragments and gases that descend a volcano's flanks at speeds ranging from 10 to more than 100 meters/sec (20–200 mph). Because of their mass, high temperature, high speed, and great mobility, these flows are destructive and pose lethal hazard from incineration, asphyxiation, burial, and impact. Because of their high speed, pyroclastic flows are difficult or impossible to escape. Evacuation must take place before such events occur. These flows have been known to move many kilometers downslope from the volcano. They typically concentrate in valleys and move rapidly out into adjacent areas where they cause damage to life, limb, and property (Wolfe and Pierson 1995).

Just as mixtures of hot volcanic gas and tephra rise into the atmosphere when the mixture is less dense than the surrounding air, mixtures of hot volcanic rock fragments and gas that are more dense than the surrounding atmosphere flow down the volcano flanks as pyroclastic flows. Such flows can originate from high vertical eruption columns, from low fountains of erupting pyroclastic material that appear to "boil over" from the vent, and from gravitational or explosive disruption of hot lava domes. The first two mechanisms operated during the explosive eruptions of 1980 at Mount St. Helens and are likely again should eruptive activity be resumed. The third mechanism, disruption of a hot lava dome, has operated at numerous times in the past at Mount St. Helens but would be significant there only if new dome growth should become established.

Driven by gravity, pyroclastic flows seek topographically low areas and beyond the steep flanks of the volcano, tend to be channeled into valleys. Pyroclastic flows from the May 18, 1980 eruption ran out only about 8 km (5 mi.) from the vent. As they impinged on Johnston Ridge, they were deflected westward down-valley and eastward to Spirit Lake. During the past 4,000 years, during which time the volcano's modern edifice formed, numerous pyroclastic flows are known to have traveled at least as far as 10- 15 km (6 to 9 mi), and at least one older flow is known to have traveled as much as 20 km (12 mi). Although the present crater geometry favors distribution of pyroclastic flows into the North Fork Toutle River valley, all flanks of a volcano are subject to pyroclastic-flow hazard during a large eruption.

Glacier Peak in Snohomish County is a 10,541 foot stratovolcano that has erupted at least a dozen times in the past 14,000 years, most recently around the 18^{th} century. Pyroclastic flows from 11,000 to 12,000 years ago traveled 15 kilometers from the volcano, and lahars were detected in areas along the Stillaguamish and Skagit Rivers more than 100 kilometers from the volcano (Beget 1983). Tephra eruptions during this time generated two tephra layers 800-1000 kilometers to the east.

Pyroclastic Surge

Pyroclastic surges are turbulent, relatively low-density (but still denser than air), mixtures of gas and rock that flow above the ground surface at high velocities similar to those of pyroclastic flows (Wolfe and Pierson 1995). Hot pyroclastic surges are generated similarly to pyroclastic flows as well as by lateral blasts and as mobile, turbulent ash clouds winnowed from pyroclastic flows. Hazards resulting from pyroclastic surges include incineration, destruction by high-velocity ash-laden winds, impact by rock fragments, burial by surge deposits, exposure to noxious gases, and asphyxiation. Like pyroclastic flows, pyroclastic surges are too fast moving to escape; evacuation must take place before they occur.

Because they are less dense, pyroclastic surges are less constrained by topography than are pyroclastic flows. Surges may climb or surmount valley walls, affecting areas well beyond the limits of pyroclastic flows. For example, pyroclastic surges surmounted Johnston Ridge and entered the drainage of South Coldwater Creek on May 18, 1980, even though the related pyroclastic flows were deflected by the steep north-facing escarpment of the ridge (Wolfe and Pierson 1995).

Lahars

A lahar is a mixture of water, ice, and sediment that is generated during and sometimes after an eruption (Wolfe and Pierson 1995). Hot gases and magma that are ejected under and on top of snow and ice fields rapidly melt the snow and ice creating a mix of tephra, sediments and solidified lava that flow very rapidly down the flanks of the volcano. Lahars are gravity-controlled flows that are channeled into valleys as they move downhill. Lahars triggered during the 1980 eruption of Mount St. Helens were 3 to15 meters deep and traveled at speeds of 20 to 40 m/sec (45 to 90 mph) down the mountain's flanks. Upon reaching flatter river valleys, they slowed down to 10 to 20 m/sec. (22 to 45 mph). Lahars typically grow in size as they move downslope by picking up sediment, water and organic materials (trees) through a process called "bulking." Volume commonly increases by a factor of 3 to 5. As lahars get farther away from their source, they slow down and flatten out destroying structures and lifelines in their path. An unusually extensive lahar originated near the top of Mount Rainier about 4,800 years before present. It swept down about 70 km through the Orting area and spread out in the lowlands around Tacoma. It formed a lobe about 30 km long and 5 to 17 km wide. A lahar of this size, if it occurred today, would do immense damage to the local population centers, infrastructure, and the environment.

The potential route of a lahar off Glacier Peak could go into the North Fork of the Sauk River within the Darrington Ranger District, an area that was hard hit by the October/November 2003 flood events. The Town of Darrington would be threatened by a significant lahar from an eruption of Glacier Peak; this mudflow would primarily impact the North Fork of the Sauk and North Fork of the Stillaguamish systems (Waitt et al. 1995).

Lateral Blast

A lateral blast is a volcanic explosion that has a significant low-angle component and is typically confined to less than 180 degrees of circumference. Lateral blasts can generate significant pyroclastic flows and can launch large particles or "ballistic projectiles" (Wolfe and Pierson 1995) many kms from the mountain. Mount St. Helens erupted with a massive landslide that collapsed the magma body and attendant hydrothermal system within the mountain. This collapse resulted in a huge lateral blast that knocked over trees and structures for many hundreds of square km around the north side of the mountain.

Lava Flow

Lava that emanates from mountains such as Glacier Peak, Mount Rainier, or Mount St. Helens is typically quite viscous and does not usually flow far from the vent. Rather, it forms very steep-sided domes atop the mountain that lead to dome collapse, explosive eruption, pyroclastic flows, and lahars. Lava flows like those seen in shield volcanoes (e.g., Kilauea on Hawaii) do not usually occur in Cascade volcanoes, but there is evidence that fluid basaltic flows have emanated from Mount St. Helens in the past, thus it would be prudent to be aware of such possibility.

Recent research indicates that lava moving underground in dikes, upon striking mining adits, drifts, or other underground passages may move at speeds upwards of 300 m/sec making them extraordinarily dangerous to underground mine workings or storage facilities (Woods 2002). Small volcanic dikes have been seen as far east as near the Kenwanda Golf Course and the area around High Rock east of SR 203 (Snohomish County 1989).

Volcanic Gases

All magmas contain gases that are released both during and between eruptions. Volcanic gases (VOG) consist mainly of steam but also include carbon dioxide and compounds of sulfur and chlorine (Tilling 1991). Minor amounts of carbon monoxide, fluorine and boron compounds, ammonia, and several other volcanic gases may also be present.

Volcanic gases become diluted rapidly downwind from the vent. Yet within 10 km of a vent, volcanic gases can endanger life and health, and sometimes property (Waitt et al.1995). Eyes and lungs of people and animals can be injured by aerosolized acids, ammonia, and other compounds. People and animals can suffocate in denser-than-air gases such as carbon dioxide, which pond and accumulate in closed depressions. Metals, glass, and other susceptible materials can severely corrode when bathed in volcanic gases (Waitt et al. 1995).

Volcanic Hazard Area Protection

The scientific literature reviewed above and worldwide standards of practice indicate that the best way to regulate volcanic hazards is by way of zonation. Roughly circular zones that represent decreasing risk with distance from the mountain are established based on the geologic record of past eruptive events as mapped by geologists. Each zone is mapped based on the probability of occurrence of the various hazards. So-called “flowage hazards” (pyroclastic flows and surges, lahars, and lateral blasts) are the most deadly and damaging and are typically mapped in three zones – a proximal zone of high concentration or high density flow, a proximal zone of low concentration or low density flow, and a distal zone where well-channelized lahars represent the only significant hazard. Zones 1 and 2 are subject to the full gamut of hazards as discussed above and should be regulated with the understanding that these events occur with such rapidity that it is impossible to evacuate after an eruption has begun. Evacuation must happen before an eruption. Zone 3 is different in that regulation can be limited to those areas where lahars are expected to descend. That regulation could take the form of buffers around historical lahar deposits or flows or could be a more generalized based on topographic elevation (Wolfe and Pierson 1995). Within the Sauk and Stillaguamish River System these warning zones and risks should be disclosed to owners and future owners of the riverfront properties that are subject to the area of concern.

Abandoned Mine Hazard Areas

An abandoned mine hazard area is an area underlain by abandoned mine workings including adits (a nearly horizontal mine entrance shaft), drifts (secondary passages between main shafts), tunnels, or air shafts (often nearly vertical). In Snohomish County, the County has a long history of active mining of gravel and mineral resources lands. Some of the more well known mining areas are around Monte Cristo, Granite Falls and in the vicinity of the Town of Index (Woodhouse and Wood 1996).

The Department of Natural Resources has records of known abandoned mines, the location of these are of interest to the general public only in the sense that they should be designated by a geographic location on a map and protected via fencing or posted and closed for public access (WADNR 2001).

Hazards related to the presence of underground mine workings have been studied extensively in the United States, Scandinavia, the UK, and Eastern Europe. The physical hazards that manifest in these areas are well known and mitigation of these hazards has long been practiced. In general, the underground workings are mapped during the mining process or subsequent to mine closure and the overlying surface is identified accordingly. The standard of practice is to require surface and subsurface studies in these areas to define the scope of the potential problem. Typically, when airshafts or adits are discovered they are sealed or filled to prevent unauthorized entry and to the extent possible minimize subsidence or ground settlement. Geotechnical and geophysical analyses can estimate the potential for subsidence based on depth of workings, soil or rock type, and surface and subsurface geometry. Based on these parameters, an area is defined as an Abandoned Mine Hazard Area. Appropriate geophysical studies prior to any development activity will reveal how or if development can occur in a safe manner. These studies may include downhole boring, geomagnetic surveys, sonar/echo location, laser mapping or other methods to map the subsurface terrain.

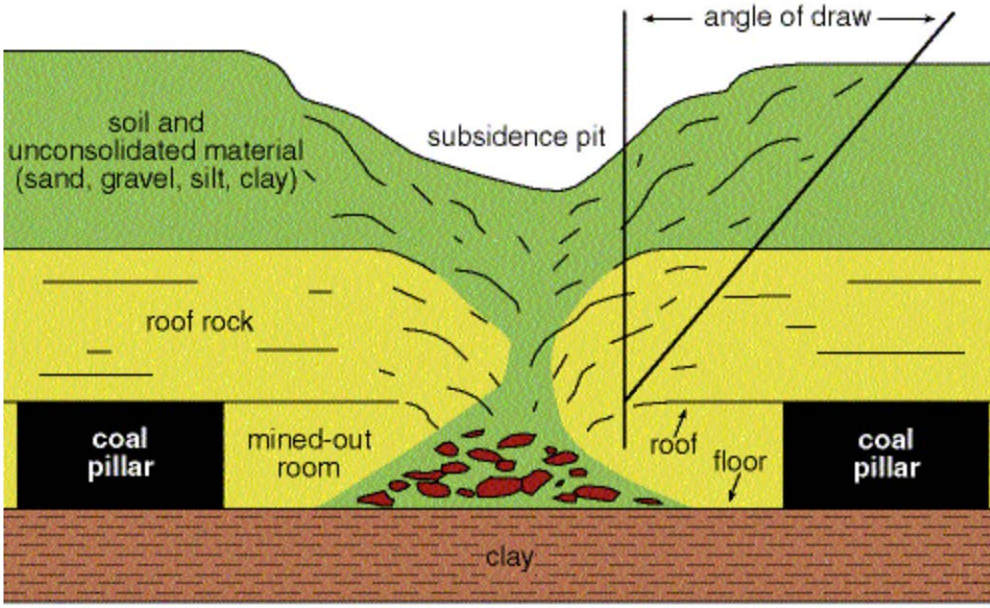
Abandoned mine hazard areas were mapped by the Washington State Department of Natural Resources, Division of Geology and Earth Resources; they are the agency that is ultimately responsible for the regulation of mining in the State. Not all mine workings will appear on the available maps, either because the mines were worked prior to 1900 or because they were small and unregistered by the State. When unmapped abandoned mines are located they may be added to the Counties' and State's GIS Inventory.

Abandoned Mine Hazard Area Functions

Subsidence, in the context of underground mining, is the lowering of the Earth's surface due to collapse of bedrock and unconsolidated materials (sand, gravel, silt, and clay) into underground mined areas.

There are two types of subsidence: (1) pit, also called sinkhole or pothole; and (2) sag or trough. (The term "sinkhole" more properly refers to solution collapse features in limestone or karst.) Pit subsidence is characterized by an abrupt sinking of the surface, resulting in a circular steep-sided, craterlike feature that has an inward drainage pattern. It is associated with roof collapse of mines that have total overburden (overlying unconsolidated material and rock) of less than 165 feet, weak roof rock of shale or mudstone, and a ratio of unconsolidated-material thickness to rock thickness of less than 1:2. Pit subsidence does not occur where the thickness of the unconsolidated overburden is more than 90 feet. (Price et al.1969) Sag subsidence is a gentle, gradual settling of the surface. It is associated with pillar crushing or pillar punching (discussed below) of deeper mines (overburden of more than 75 feet) (Goodman 1989). Sag-subsidence features may fill with water if the surface of the subsidence intersects the water table. Pit-subsidence features generally do not hold water because the pit drains into the underlying mine.

Figure 4.0 Cross Section of Mine Roof Collapse (Crowell 1995)



Diagrammatic cross section of typical subsidence resulting from mine-roof collapse. No scale implied.

Mine subsidence is controlled by many factors, including height of mined-out area, width of unsupported mine roof, thickness of overburden, competency (strength) of bedrock, pillar dimensions, hydrology, fractures/joints, and time. The vertical component of subsidence is proportional to the height of the extraction area. Generally, the vertical component of subsidence does not exceed the height of the mine void. However, piping (subsurface erosion by water washing away fine-grained soil) of unconsolidated material can create a cavity deeper than the height of the mined area.

The area of mine subsidence increases proportionally with increasing width of unsupported roof rock. The potential area of subsidence is equal to the extraction area plus an area surrounding the extraction area measured by an angle up to 35 degrees, called the angle of draw, from the vertical at the edge of the extraction area. For example, roof collapse in a mine 160 feet deep could cause subsidence more than 75 feet beyond the edge of the mine. The deeper the mine, the larger the area potentially affected by mine subsidence at the surface.

The vertical component of subsidence decreases with increasing depth or thickness of overburden, especially bedrock. As the roof rock sags, ruptures, and eventually collapses into a mined-out area, the roof rock rotates, twists, splinters, or crumbles as it falls, resulting in incomplete compaction. In other words, the mine void is not completely filled during a mine-roof collapse. Because bedrock collapses with incomplete compaction, the deeper the extraction area, the smaller the vertical component is at the surface.

Mine subsidence is related to the strength or competency of bedrock, which is a measure of a rock's load-bearing capacity. Sandstones and limestones are capable of withstanding greater loads than are shales and mudstones. Therefore, sandstones and limestones can span larger unsupported distances or support thicker amounts of overburden before failing (Jumikis 1983.)

Mine subsidence increases as the size of the supporting pillars decreases. In room-and-pillar mining, about 50 percent of the seam is left in place as pillars for roof support. However, coal operators in the nineteenth and early twentieth centuries commonly mined the pillars, partially or wholly, as an area of the mine was abandoned. Roslyn and Black Diamond are communities in this state where this was done on occasion. Complete mining of a pillar is called pillar robbing. Reducing the size of a pillar is called pillar slicing. Creating small, multiple pillars out of a single, large pillar is called pillar splicing. Mining the pillar increases the width of unsupported roof, which increases the likelihood of subsidence. Also, diminishing the size of a pillar increases the chance of pillar crushing or pillar punching and increases the chance of mine-roof collapse. Pillar crushing results when the weight of the overburden exceeds the load-bearing capacity of the pillar and it is crushed. Pillar punching results when the weight of the overburden exceeds the load-bearing capacity of the floor rock, and the pillar is pushed downward into the floor. In pillar punching, the floor rock is generally soft, plastic clay that flows upward into the mine void, a phenomenon miners term a “squeeze.”

Mine subsidence is affected by water circulation or the fluctuation of water level in a mine. Some underground mines remain dry after abandonment; many others fill with water. Circulating water in an underground mine can deteriorate roof support or the roof rock. Because of its incompressibility, water provides support to the roof of a mine that is filled with water. However, the likelihood of roof collapse may be enhanced or accelerated in mines where the roof rock is repeatedly saturated then left unsupported by fluctuating water levels (either by seasonal weather conditions or intentional pumping) and where the pillars of rock are eroded by flowing water.

The likelihood of subsidence increases where fractures (joints) intersect the mine roof. Fractures or joints are natural planes of weakness where collapse of the mine roof is likely to occur. Fractures also may allow the subsidence to extend beyond the limit of the mined area.

The length of time for mine subsidence to occur increases with increasing depth of mining and increasing competency of overburden. The type and amount of roof support in addition to pillars left in the mine also affect subsidence. Most early underground mines in Washington used wooden timbers as additional roof support. By the mid-twentieth century, roof bolting was another type of roof support being used in the mines. With time following abandonment of an underground mine, these types of roof support eventually rot or deteriorate, allowing subsidence to occur. Because of the complexity of the variables which contribute to mine-related subsidence, no acceptable system exists which is capable of accurately predicting the time or amount of subsidence in a variety of geological settings, especially for mines that have an irregular pattern of room-and-pillar mining. A good example of the rate of deterioration of timber and roof support systems is readily seen on the Iron Goat Trail and Tunnel System, this particular site is located up Highway 2 near Stevens Pass and is designated a National Civil Engineering Landmark (ASCE Seattle Section 1983, 2000).

In addition to subsidence above a mine, the collapse of improperly stabilized mine openings presents a great risk to public property and safety. The collapse of an improperly sealed shaft may equal the original depth of the shaft. In 1977, an improperly stabilized shaft to a coal mine abandoned in 1884, collapsed underneath a garage in a residential neighborhood in Youngstown, Ohio, leaving a 115-foot-deep opening. This shaft was originally 230 feet deep. Fortunately, there was no loss of life or personal injury associated with this collapse, but this shaft collapse illustrates the potential for life-threatening situations due to collapse of mine openings.

Within Snohomish County several sinkholes developed and collapsed in the Eastmont neighborhood causing a vehicle and garage shed to be lost as well as the usable rear yard of the property for several years (Dennis 2000; Johnson 2000), fortunately no one was injured.

Abandoned Mine Hazard Area Protection

Literature review indicates that these hazard areas should have protection boundaries applied to them that have the same effect and function as buffers. The boundaries should be established based on the known physical dimensions of the abandoned mine and on the stratigraphy of the beds or rock in the area. As described above, the size of the boundary is directly related to the depth of the mine. The actual angle of draw that is applied will vary depending on the attitude of the underlying beds or rock surfaces and on the surface (i.e., sloping vs. horizontal). The actual location of these boundaries must be established on a site-specific basis by a trained engineering geologist or geotechnical engineer.

Repair work to ameliorate damage due to subsidence events should fill or block adits and airshafts as they are discovered, temporary fencing and signage may be necessary until such time as the abandoned mine is properly closed or filled in.

Summary

A review of scientific literature about the five geologic hazard areas reveals that these areas pose potential physical hazards to life, limb, property, or the environment. There are specific soil types, slope gradients, climatic conditions, and many other factors that dictate the degree of hazard associated with any particular site. Site-specific review of these conditions is the most effective method to accurately evaluate the potential for development of a hazardous condition. In general, the site-specific review must be carried out by a professional with technical knowledge related to the geologic or engineering subdiscipline in question (e.g., slope stability or abandoned mine hazard potential). Certain types of geologic hazards, buffer zones of varying, but conservative widths may be substituted for site-specific evaluation, these setbacks would at least be equivalent to that described in the International Building Code. Among these are landslide hazard areas, volcanic hazard areas, and abandoned mine hazard areas. Current science-based and fully implemented construction standards and Best Management Practices (BMPs) can be used to ameliorate the potential hazards.

There is much scientific literature on channel dynamics, movement, and factors affecting channel migration. There are few examples from scientific literature that define CMZs with specificity or evaluate the effectiveness of various CMZ delineations in reducing erosion or flood hazard due to channel migration. Some key CMZ terms and definitions are not based specifically on scientific research, such as the selection of a timeframe to determine the lateral extent of a CMZ. Currently there is no national standard, consensus definition, or single method to delineate CMZs, as there is for flood inundation hazard (FEMA 1999). However, the literature examples that do address CMZs specifically, in combination with the large body of literature on channel dynamics provide an adequate scientific framework to define and delineate CMZs.

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Chapter 5 – Wetlands

Provided on CD

The wetlands chapter is adopted in its entirety from the Washington State Department of Ecology's *Freshwater Wetlands in Washington State, Volume 1: A synthesis of the science*. Because of its length it is provided on CD. The citation for this chapter is:

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Appendix A
Stormwater Mitigation Measures

Stormwater Flow Rate and Volume Control

Surface detention

This section discusses design methods and criteria for stormwater flow rate and volume control, including hydrologic modeling methods and infiltration systems. Hydrologic modeling methods are tied to surface detention design standards and are used for designing infiltration systems.

Stormwater detention systems alter the stormwater hydrograph by capturing some or all of the stormwater runoff generated by a rainfall event and releasing the volume as surface runoff at a controlled rate through a set of orifices or a weir. Both open ponds and enclosed structures (e.g., vaults, tanks, and pipes) are used for surface detention. Detention facilities do not address the increased stormwater volume that may be generated by development, although they can be designed to function as combination detention / infiltration facilities if soil conditions allow it.

The Department of Ecology's 1992 Stormwater Management Manual for the Puget Sound Basin required the use of a single-rainfall-event hydrologic model to calculate pre-development and post-development runoff, and, if stormwater infiltration was not feasible on site, required the following post-development peak flow rate conditions based on selected storm statistics:

- 100-year/24-hour storm – post-development peak flow rate = pre-development peak flow rate;
- 10-year/24-hour storm – post-development peak flow rate = pre-development peak flow rate; and
- 2-year/24-hour storm – post-development peak flow rate = 50% of pre-development peak flow rate.

Ecology's intent with the '50% of the 2-year flow' standard was to prevent stream channel destabilization by controlling sediment transport, based on work cited above, e.g., Sidle (1988) and Booth (1990). While the flow control approach in the 1992 Manual provided significantly more environmental protection than previous standards, it is now widely understood to have some fundamental flaws, among them:

- It requires the assumption that flow statistics correlate perfectly to rainfall statistics, e.g., that the X-year peak flow correlates exactly to the X-year, 24-hour peak rainfall depth. The results of continuous simulation models such as HSPF show that this assumption is not necessarily true;
- It assumes that controlling the peak flow from a storm, i.e., preventing the peak flow from exceeding some standard, will by itself result in no change of channel instability. This is not true, since the peak flow standards do not address the increase in total runoff volume, which translates into an increase in total time that elevated stormflow rates will work on the channel to transport sediment;

- It does not address the reduction in total rainfall infiltration and interstorm runoff that typically results from development; and
- It ignores the possibility that other negative environmental effects will occur even if channel stability is achieved.

Booth (1991) discussed the shortcomings of using a single-event model and a peak flow detention standard, and discussed the use of a 'flow duration control' standard. Instead of limiting the peak flow rate, a duration-control standard limits the total amount of time in a relatively long period (e.g., months) during which the flow rate could exceed selected flow rates of concern. It should be noted that the use of flow duration control standards requires the use of continuous simulation hydrologic models such as HSPF. In 1991, there were relatively few people who were proficient in using HSPF, there was no widely-accepted flow control design methodology for using HSPF outputs, and a single HSPF run required hours of computing time from the typical desktop computer of the age.

Booth and Jackson (1997) discussed the shortcomings of flow duration control standards, primary among which is the assumption that for all streams there is a flow rate below which no sediment transport occurs, so that a flow rate below this index rate would not cause channel incision regardless of the flow duration. Booth and Jackson (1997) state that "(F) or gravel-bed stream channels, this threshold discharge is real and can be determined on a site-specific or generic basis. In sand-bedded channel, however, the threshold of sediment motion occurs at impracticably low discharges, and so increases in the net transport of bed material virtually unavoidable in such systems." During this time period, much research in the Puget Sound area was focused on determining more robust and protective flow statistics to use for regulation, such as the correlation between "unstable" stream channels and streams for which the frequency of the predevelopment 10-year peak flow equals that of the post development 2-year peak flow (ibid.)

In 1998 King County promulgated a stormwater manual, and associated regulations, based on flow duration control standards to mitigate impacts from stormwater flow. The Washington State Department of Ecology followed suit in 2001 with the Western Washington Stormwater Management Manual. An HSPF-based hydrologic model – the Western Washington Hydrologic Model, or WWHM - was developed by Ecology and serves as the basis for hydrologic design under the 2001 Ecology Manual. The WWHM is based on climatic data and other input data from a number of locations in western Washington.

In 2005, Ecology released the 2005 Western Washington Stormwater Manual, which is much the same as the 2001 Manual but which has some key changes, including:

- providing an exemption from the flow control requirement for discharges to certain rivers and large lakes;
- allowing the pre-development land cover condition to be modeled as the existing site condition in basins that have been highly urbanized for an extended period of time (this applies to sizing flow control facilities);
- deleting the instructions for development of single event hydrographs, and deleting single event hydrograph-based approaches for sizing flow control and most treatment facilities;

- updating the design procedures for sizing infiltration and filtration systems with references to use of the Western Washington Hydrology Model (WWHM) and to design criteria and steps developed by Dr. Joel Massman;
- correcting hydraulic design criteria for biofiltration swales; and
- inserting guidance concerning how to represent certain low impact development techniques within the Western Washington Hydrology Model (WWHM) so that it predicts flow reduction benefits from use of those techniques.

The issue of appropriate flow control measures for urbanized areas has been examined by several authors. The general question is whether surface flow control measures such as detention ponds, which are intended (ideally, at least) to prevent streams from exhibiting the effects of urbanization, are in fact effective or useful measures to employ in 'urbanized' watersheds. James et al. (1987) demonstrated that detention ponds that serve small areas in a watershed and those located in upper areas of a watershed may not be effective at controlling channel degradation in the larger streams of the lower watershed due to superposition of hydrographs. They asserted that planning is essential to determine the effect of multiple detention ponds in a watershed. Finkenbine et al. (2000), in a study of urban watersheds in the area of Vancouver, B.C., asserted that "stormwater detention ponds…are concluded to have few hydrological benefits if constructed after a stream has reached its urban equilibrium." This conclusion was based on the observation of reduced fine sediment in the stream beds and increased intragravel dissolved oxygen. Hartley et al (2001), in their critique of the conclusions drawn by Finkenbine et al. (2000), recommended the continued use of detention ponds to reduce the frequency of bed scour and large woody debris mobilization.

Maxted and Shaver (1998) measured indices of physical habitat and biota in eight Delaware streams below the discharge point of detention ponds in areas of at least 20% impervious cover, and measured the same indices at thirty-three streams in areas with no stormwater controls and varying degrees of urbanization. These two pools of data were compared to data from three reference sites. Of the eight detention ponds, three were designed to control peak flow rate from the 2-year, 10-year, and 100-year storms and to retain the first inch of runoff for 24 hours, four were designed to control peak rate from the 10-year storm, and one was an in-stream pond. Based on a composite of the six biological metrics used in the study, the overall macroinvertebrate community was not significantly different between sites adjacent to detention ponds (pond sites) and sites without ponds, and the composite biological index scores for both types of test sites were less than 40% of the reference site scores, indicating significant biological degradation. The degree of urbanization did not affect the biological index scores at the pond sites. Alternatively, four of the eight pond sites had Habitat Comparison Index (HCI) scores within 90% of the composite HCI for the reference sites, while only six of the thirty-three non-pond sites met this criterion. Maxted and Shaver assert that in addition to the lack of protectiveness of peak-flow control facilities, other watershed factors such as ongoing construction impacts and degraded riparian zones contributed to the reduced habitat and biological index scores.

Infiltration

Trenches, swales, and drainfields

The standard systems for stormwater infiltration are constructed depressions, trenches or drainfields, similar in structure to those used for wastewater disposal. Studies about the hydrologic performance of infiltration systems that have been performed in the Puget Sound area are referenced in the 2001 Ecology Stormwater Manual, Volume III.

Massman (2003) performed full-scale "flood tests" conducted at four infiltration facilities in western Washington. Lateral flow along the sides of the ponds could be significant. More efficient designs might require a larger ratio of side area to bottom area, consequently maintenance activities should be considered for the sides as well as the bottom of the pond. Saturated hydraulic conductivity values estimated from measuring air conductivity and from regression equations derived from grain size parameters were compared to full-scale infiltration rates for 15 sites in western Washington. The estimated values for saturated hydraulic conductivity were up to two orders-of-magnitude larger than the full-scale infiltration rates for some sites and were two orders-of-magnitude smaller at others. These results show that infiltration rates cannot be reliably estimated on the basis of soil properties alone; information related to the hydraulic gradient is also important.

Aside from the reduced area available for infiltration due to the construction of impervious surfaces, development typically results in the compaction or removal of the upper soil layers, which reduces infiltration capacity of the remaining soil (Booth et al. 2002; Chollak and Rosenfeld, 1997; Kosti et al., 1995). This effect also significantly reduces the ability of the soil to remove dissolved metals (Minton, 2002a). Other factors that may limit the long-term performance of these systems are clogging due to sediment input, or biological fouling, as described by Warner et al. (1994). Clogging due to sediment is addressed by the pretreatment requirements of the 1992 and 2001 Ecology stormwater manuals.

Permeable pavement

Permeable pavement, either asphalt or carbonate-cement based, is essentially a specialized mixture of the basic material containing voids that can convey water. The two factors controlling the use of permeable pavement as an infiltration system are the long-term hydraulic capacity of the paving material, and the infiltration capacity of the underlying soil.

Booth and Leavitt (1999) documented the pollution removal capability and hydraulic performance of four types of permeable pavement in comparison to standard asphalt pavement at a municipal building parking lot in Renton, WA. The test site was constructed in 1996, and data were gathered in the year following. The native soil at the site is a deep and very permeable sand, so overall infiltration capacity of the pavement/soil system would be limited by the pavement. Booth and Leavitt observed no surface runoff from the permeable pavement. Brattebo and Booth (2003) reevaluated hydraulic performance at the same pavement system during fifteen storms in the winter of 2001-2002. Virtually all water infiltrated for every observed storm; the most significant surface runoff event occurred during a 121-mm/72-hour storm, in which 4 mm of surface runoff was generated from one type of pavement.

A porous top paving course has been used in Europe and by the State of Oregon Department of Transportation. The porous top course, known in Oregon as an open graded friction coat (OGFC), is laid over a standard (and essentially impervious) base. While the primary reasons for using an OGFC are traffic noise reduction and visibility improvement through spray reduction, the porous surface layer filters particles and attached pollutants from stormwater, which can be removed by vacuum sweeping. The stormwater moves laterally to the shoulders where additional treatment may occur. While not proven, the concept likely reduces runoff, particularly of summer storms (Minton, 2002b).

St. John and Horner (1997) reported that porous asphalt shoulders installed on a two-lane highway with a three-day average daily traffic rate of 9,000 vehicles per day significantly reduced wet-season storm volumes, relative to runoff generated by standard asphalt shoulders.

Vegetated Roofs

Vegetated roofs, commonly used in Europe for decades, have received significant attention in the U.S. in the past several years. Runoff monitoring was conducted for a nine-month period in Philadelphia PA at a pilot-scale vegetated roof with a thickness of less than three inches (U.S.E.P.A., 2000). In this period there were 44 inches of rain and less than 16 inches of runoff.

Monitoring of four storms (two in March, 2001, and two in August, 2001) at a full-scale commercial building vegetated roof in Portland Oregon showed between a three-fold and nine-fold reduction in per-storm runoff volume (City of Portland 2001).

Beyerlein et al. (2004) modeled the performance of a hypothetical ten-acre flat vegetated roof with eight inches of soil using Washington State’s Western Washington Hydrologic Model (WWHM) and long-term rainfall and pan evaporation data for five cities: Vancouver, Bellingham, Seattle, Olympia, and Port Angeles. They determined the reduction in stormwater detention storage volume using the detention sizing module of WWHM, which incorporates the flow control standards of the 2001 Ecology Stormwater Manual. The results showed detention volumes were reduced between 17% and 31% as compared with the volumes required for a standard impervious roof. Beyerlein et al. attributed the difference between these results and those from the studies in Portland and Philadelphia to the fact that detention storage volume as determined by WWHM is typically controlled by winter storms that occur when potential evapotranspiration is lowest in western Washington. Beyerlein et al. also modeled storage volume reductions using rooftop detention, and found that the storage requirements were slightly lower than the corresponding values calculated for green roofs, which they attribute to slightly higher evapotranspiration from the open water surface. As noted previously, ET in the winter has not been field-tested for urban landscapes in the Puget Sound region, so the effects of wind on ET as measured by Blight (2002) are not known.

Low Impact Development

In recent years, the term “low impact development” or LID, has been used by many to refer to a wide variety of stormwater management measures, for both flow control and pollution control. Prince Georges County, MD has championed LID research and implementation for the past two decades. Prince Georges County (2002) provides the following definition:

> *LID is an innovative technological approach to stormwater management and ecosystem protection where hydrologic controls are integrated into every aspect of a site’s design to mimic the predevelopment hydrologic regime. It is not a growth management strategy nor does it heavily rely on density restrictions, rezoning, clustering or conservation measures. Instead, LID focuses on how to engineer the built environment to maintain ecosystem and hydrologic functions.*

> *LID uses new site planning/design principles and a wide array of micro-scale management practices to create a hydrologically functional and environmentally sensitive landscape...LID's goal is not to mitigate development impacts but instead to recreate and preserve a watershed's hydrologic cycle.*

LID relies heavily on infiltration systems, especially those that are vegetated, and the use of multiple smaller stormwater systems in a development (sometimes several on each lot) as opposed to a single system that receives the collected and concentrated runoff from the development.

One of the most well-known types of LID systems for flow control is the 'bioretention' facility, which consists of an infiltration trench, usually with an underdrain and filled with a mix of soil that provides pollution removal while not inhibiting water movement through the system, and planted with a variety of shrubs, small trees, and other plants (see Prince George's County 1999 and 2002). With regard to flow control, the factors determining overall performance are the infiltration capacity of the native soil, the detention capacity of the soil in the trench (a function of the trench volume and the soil porosity), and any evaporation or ET that takes place. Stormwater management effects of ET in the Puget Sound region are discussed above. Infiltration capacity of the native soil has nothing to do with the bioretention system itself. Hydrologic performance of a bioretention system in Maryland is discussed by Davis et al. (1998).

The City of Seattle, WA, constructed a system that is in essence a bioretention system in a street right-of-way. The system consists of a roadside swale filled with organically amended soil, in which a perforated drain was installed above the trench bottom so that some water is retained before the drain becomes functional. Water can also be held in the amended soil. The underlying soil is mostly glacial till but there is some sand as well. Approximately 2.3 acres of road and residential development drains to the swale. During the period between January, 2000, and January, 2001, the system retained all of the dry-season runoff and 98% of the wet-season runoff, and was capable of fully attenuating approximately 0.75 inches of rainfall on the catchment area (Horner, R., et al. 2002)

The Low Impact Development Technical Guidance Manual for Puget Sound (Puget Sound Action Team / Washington State University Pierce County Extension, 2005) contains LID information for site assessment, site planning and layout, vegetation protection and maintenance, clearing and grading, and flow control and treatment methods. It also contains information on hydrologic modeling input parameters for LID flow control measures; this same information was also contained in the 2005 Ecology Stormwater Management Manual for Western Washington.

Soil Amendments

As noted above, development tends to reduce infiltration by reducing both the depth and infiltration capacity of the soil column. Recent studies such as Chollak and Rosenfeld (1997) and Kosti et al. (1995) have focused on the use of organic soil amendments such as compost. Kosti et al. measured surface runoff and subsurface runoff from seven test plots of glacial till soil containing differing amounts of compost. During natural storms from December 1994 to June 1995, two plots containing compost generated 53% and 70% of the total runoff volume generated by a control plot with no compost. The surface runoff hydrographs were attenuated in the compost plots as well. It should be noted that using amended soils in urban lawns can also have the benefits of reduced fertilizer requirements and reduced dry-season irrigation requirements. These were primary motivators for the City of Redmond to initiate the research, since it discharges stormwater to a lake with a phosphorous limitation, and it purchases all of its potable water from the City of Seattle.

Land Use Controls

The research by Booth (1990) and others also led to the question of thresholds below which surface detention might not be needed. King County (1994) evaluated a variety of alternative rural development scenarios in the Issaquah creek watershed, and found, for till soils, that retaining 65% forest cover satisfied the criterion of keeping the 2-year post development discharge below the 10-year forest-cover discharge. Booth et al. (2002), in discussing the King County watershed plans of this era, point out that the commonly-chosen rural resource protection thresholds of 65% forest cover retention coupled with 10% maximum EIA "mark an observed transition in the downstream channels from minimally to severely degraded stream conditions." It should be noted that it is not difficult to meet these standards for a typical single-family house and attendant impervious surfaces on a typical 'rural residential' five-acre parcel using standard design and construction methods, provided that adequate forest cover is present at the outset. However, at an urban single-family residential density of four to six dwellings per acre, the typical lot size is in the realm of 5,000 square feet, making it much more difficult to meet the 10% maximum EIA criterion, let alone the 65% forest retention criterion.

Stormwater Pollution Control

Minton (2002a) provides a thorough discussion of treatment mechanisms and their application in stormwater treatment. The American Society of Civil Engineers (ASCE) and the United States Environmental Protection Agency (USEPA) jointly prepared a database of stormwater treatment system performance data (ASCE/EPA 2003). The Washington State Department of Ecology, in concert with stormwater professionals from the Puget Sound developed a protocol for evaluating 'innovative' treatment systems; test results and other information are posted on the associated web site (http://www.ecy.wa.gov/programs/wq/stormwater/newtech/index.html).

Pollutants may be removed from stormwater by a variety of mechanisms, including gravimetric separation (sedimentation and flotation), precipitation, coagulation, inert media filtration, sorptive media filtration, and degradation or transformation of pollutants by physical, chemical, or biological processes (Minton, 2002a).

Ponds, Vaults, and Catch Basins

Catch basins can remove sediment in the size range of sand (grain size > 250um) at flows typical of storm flow rates, although they are less effective at removing smaller size particles such as silts and clays (Aronson et al., 1983; Leif 1998; Lager et al. 1997). The sand thus captured, if removed from the drainage system before it is transported to receiving waters, may reduce the load of adsorbed pollutants such as metals and pesticides.

Many detention facilities (both open ponds and enclosed vaults or tanks) are designed to provide flood control or streambank erosion control, and are not specifically designed to remove pollutants from stormwater. However, these facilities likely provide some modest reduction of sediment and particular pollutants. Other detention facilities, known as 'extended treatment detention' facilities, are designed to provide additional detention time beyond that required for flow control standards, although they are designed to empty fully. Detention facilities can also be designed as ‘wet ponds’ or ‘wet vaults,’ which means that they contain a permanent volume of water in the system for pollution removal. Extended treatment detention systems are specifically designed to remove pollutants, although they are not likely as effective as wet ponds or vaults. Studies of pollution removal in detention ponds in the Puget Sound region include King County (1995), Comings (1998), and Kulzer (1989). Other useful studies include Driscoll (1986), Gain (1996), Kantrowitz and Woodham (1995), Lawrence et al. (1996), Stanley (1996), Walker (1987), Whipple (1979), and Wu et al. (1996). These studies show that detention ponds can remove total suspended solids, total nitrogen, metals, and phosphorous. However, some of the studies showed a net release of some of these pollutants. Surface wet basins such as ponds and wetlands also remove dissolved pollutants, although their long-term performance in this respect is problematic particularly with respect to dissolved phosphorus (Minton, 2004a).

Minton (2002a) discusses the difficulties in designing appropriate sampling strategies to comparing data from different treatment system evaluation studies. Detention ponds can pose a particular problem since they often have a storage volume greater than the influent volume from many storms, so samples of influent and effluent from a single storm do not represent batch treatment of a single test volume of water.

A Florida study of the migration of soluble metals through sediments accumulated in the bottom of highway-runoff detention ponds showed that most of the metals are retained in the top 15-25 centimeters, and that removal of accumulated bottom sediments approximately every 25 years would be sufficient to minimize the potential of groundwater contamination (Yousef and Yu, 1992). However, this study did not indicate the native soil type or sediment size distribution, which would affect the results.

Media Filtration / Adsorption Systems

Inert media filtration, such as sand filtration, is an old water treatment technology that has been applied to stormwater. Useful references include City of Austin, TX (1990), Horner and Horner (1995), and Bell et al. (1995). These studies show that sand filters can remove total suspended solids (TSS), metals, biochemical oxygen demand (BOD), petroleum, total nitrogen, and phosphorous. Nitrate concentrations can increase in the effluent due to nitrification in the filter, if hydraulic residence time or filter conditions do not allow denitrification. Recent studies suggest that sand filters remove dissolved metals (California Department of Transportation, 2004; Minton, 2004), although the removal mechanisms and the longevity of the removal is not yet understood (Minton, 2004b).

Minton (2002a) cites various studies showing the pollution removal effectiveness of sand coated with iron oxide and sand mixed with iron wool or calcitic lime. Wanielista and Cassagnol (1981) demonstrated that various amended sand media reduced BOD and TSS concentrations in detention pond effluent, and that some nitrogen removal took place in the filters as well.

Stormwater filtration using peat mixed with sand is effective at removing metals (Clark et. al, 1998). Severe clogging in a sapric peat/sand filter in Minnesota demonstrated the importance of using hemic or fibric peat (Tomasek et al. 1987). These hydraulic problems can be avoided by using commercially available peat pellets.

Leif (1999) and CSF Treatment Systems (1994) demonstrated that filtration using mature processed leaf compost effectively removes TSS and total metals. Phosphorous concentrations were higher in the effluent than in the influent in the tests by Leif (1999), probably due to degradation of vegetative material washed onto the filter and bird manure deposited on the filter bed. Since compost serves as a cation exchange medium, one would expect metals removal by adsorption, but not removal of phosphorous or nitrate, which are anions.

Minton (2002a) cited various studies showing the effectiveness of zeolite minerals as a filtration medium to remove metals by cation exchange and phosphorous by anion exchange in cases where the zeolites were amended to improve anion exchange capability. Minton also cited the studies on the use of activated alumina, cationic and anionic polymers, synthetic resins, and other media.

Catch basin inserts (CBIs) received much attention in the early 1990s as a potential alternative to 'end-of-pipe' treatment. An initial study combining field and bench-scale evaluations of various manufactured CBIs in the Puget Sound area showed that the units tested were not effective at removing sediment in the silt/clay size range, total and dissolved metals, or total phosphorous (Catch Basin Insert Committee, 1995). One of the CBIs tested removed an average of 30% TPH (used motor oil) at influent concentrations of 20 mg/L to 90 mg/L, by means of adsorption onto the polypropylene material contained in and composing the body of the CBI. A primary and inherent shortcoming of CBIs is their small size relative to the typical storm flow used for filter design purposes. However, there has been a resurgence of interest in inserts with new products that may overcome the deficiencies of "first generation" products.

The Washington State Department of Transportation (WSDOT) developed a combination biofiltration/organically-amended soil infiltration system which they named the 'Ecology Embankment' or 'Ecology Ditch' (which is two Ecology Embankments put together to form a swale). Full-scale field test results on an Ecology Embankment showed significant removal of TSS, total and dissolved metals, and total phosphorous (Washington State Department of Ecology, 2003).

Infiltration

A study of several stormwater infiltration system designs in Pierce County, Washington, showed that infiltration of stormwater through a biofiltration swale underlain by six inches of imported topsoil reduced total copper concentrations by 47%, total lead concentrations by 79%, and total zinc concentration by 50% (Tacoma-Pierce County Health Department / Pierce County Public Works Department, 1995). Nineteen storm events were monitored over four years in the study. In contrast to these results, the study also found elevated concentrations of these metals in groundwater under infiltration systems that discharged directly to the gravelly native soils without any other treatment. These results together demonstrate the importance of properly absorptive soil or treatment medium, but also the efficacy of a relatively shallow layer of such soil in removing metals.

Hathhorn and Yonge (1996) investigated the potential for groundwater pollution from stormwater infiltration systems using bench-scale systems containing soils found in Washington State and organic soil amendments. They found that copper and zinc tended to be removed by association with organic material, while adsorption onto soil minerals due to cation exchange was the dominant removal mechanism for cadmium and lead. Extensive reviews of the potential for and confirmation of groundwater contamination are provided in Minton (2002a) and Pitt (1996).

Permeable Pavement

Booth and Leavitt (1999) documented the pollution removal capability and hydraulic performance of four types of permeable pavement in comparison to standard asphalt pavement at a municipal building parking lot in Renton, WA (see description of test facility in Section x.3.1 above). Tests were conducted in 1996. Infiltrated water was collected after passing through on to two inches of medium sand leveling course and about inches of pit-run sand and gravel subgrade, so the pollution removal capability of the pavement materials alone is unknown. Total copper and total zinc concentrations in the sampled infiltrate were significantly lower than corresponding concentrations in runoff from the asphalt. Brattebo and Booth (2003) reevaluated pollution removal at the same pavement system during nine storms in the winter of 2001-2002. Again, infiltration had a dramatic effect on water quality. Toxic concentrations of copper and zinc were present in 97% of the asphalt runoff samples, and in 14% of the infiltrate samples. A comparison of the data from the two studies showed that zinc concentrations increased with statistical significance in the later study for both permeable pavement and asphalt, whereas copper concentrations in infiltrate from two kinds of permeable pavement were significantly decreased in the later study (Brattebo and Booth, 2003).

St. John and Horner (1997) reported that porous asphalt shoulders installed on a high-traffic highway removed over 90% of the solids and total metals in runoff generated by adjacent standard asphalt shoulders.

Biofiltration swales and vegetated strips

Biofiltration swales and vegetated strips have been widely studied in the Puget Sound region and elsewhere. Biofiltration swales are treatment systems consisting of vegetated swales that receive stormwater collected and concentrated from an area, whereas vegetated strips are designed to receive unconcentrated sheetflow, such as would be generated in the ideal case from a crowned roadway section. As noted by Minton (2002a), the term ‘biofilter’ is likely a misnomer as the settling of sediment and attached pollutants is likely the dominant removal mechanism, not filtration by the vegetation.

Local biofiltration studies include Goldberg et al. (1993), Kulzer et al. (1992), King County (1995), and Horner (1988). These studies generally showed that TSS and total metals are removed in biofiltration swales, with phosphorous removal possible to a more variable degree. Field inspection of thirty-nine biofiltration swales in King County, WA, found only nine to be in ‘good’ condition, i.e., having relatively complete and uniform vegetation cover (King County 1995). Another unofficial earlier study found similar results (Minton 2004c). While unvegetated systems that contain standing water may remove pollutants through settling under low flow conditions, sediment would likely be resuspended in these systems during higher flows (King County, 1995).

Newberry and Yonge (1996) found that a vegetated strip removed significant amounts of TSS and metals from simulated stormwater. The WSDOT Ecology Embankment listed in the document by Washington State Department of Ecology (2003) was a vegetated strip with underlying soil intended to promote infiltration and pollutant removal by soil treatment as well as biofiltration.

Cammermayer et al. (2000) documented the effectiveness of different levels of maintenance on improving and maintaining pollutant removal performance on vegetated highway ditches that were not designed as biofiltration swales.

Bioretention

Davis et al. (2001) studied the characteristics and performance of bioretention systems for the removal of several heavy metals (Cu, Pb, Zn) and nutrients (P, TKN, NH_4^+-N, NO_3^--N) from a synthetic urban storm water runoff using batch and column adsorption studies, along with pilot scale laboratory systems. Reduction in concentrations of all metals exceeded 90% with specific metal removals of 15 to 145 mg/m^2 per event. TKN, ammonium, and phosphorus levels were reduced by 60%-80%. Little nitrate was removed and nitrate production was noted in several cases. Davis et al. (2003) evaluated pollutant removal in pilot-plant laboratory bioretention systems and two existing bioretention facilities. Removal rates of lead, copper, and zinc were close to 100% under most conditions, with effluent copper and lead levels mostly less than 5 ug/L and zinc less than 25 ug/L. Somewhat less removal was noted for shallow bioretention depths. Runoff pH, duration, intensity, and pollutant concentrations were varied, and all had minimal effect on removal. The two field investigations generally supported the laboratory studies.

Kim et al. (2003) evaluated nitrate removal by denitrification in test columns and a pilot-scale bioretention system that were designed to promote nitrate removal through the use of continuously submerged anoxic zone with an overdrain. The pilot-scale facility achieved nitrate plus nitrite mass removals of up to 80%. It should be noted, however, that Kim et al. deoxygenated the water before it entered the denitrifying unit, and also added carbon. Denitrification in the field may be limited by the lack of carbon just like in wastewater systems (Minton 2004d). As yet, field studies have yet to confirm the benefits of this approach.

Bioretention systems may be designed with an underdrain system like a traditional filter, or without an underdrain, in which case the filter effluent infiltrates into the ground system, like a filter. The former case is most suited for use in situations where the soil is not infiltrative (e.g., some till soils). Alternatively, some native soils in Snohomish County will allow infiltration but do not have adequate treatment capacity; in these cases, bioretention systems that infiltrate may be appropriate. If the soil is both infiltrative and contains adequate treatment capacity, the use of a bioretention system may be used in combination with standard treatment infiltration as a treatment train (see following section).

Treatment Trains

A ‘treatment train’ is in essence a series of individual treatment components, each of which is intended to provide a specific function and to enhance the function of other parts of the system and the system as a whole. The concept is hardly new to water and wastewater treatment, and most of the systems discussed above are in fact treatment trains.

Corsi et al. (1999) evaluated a multi-chambered treatment train (MCTT) consisting of a grit chamber, a chamber containing tube settlers and oil-absorbing pillows, and a chamber with a mixed-media filter consisting of peat, sand, and activated carbon. The mean removal efficiency over fifteen storms for total suspended solids was 98%; for total phosphorous, 88%, and for total zinc, 91%. The mean removal efficiency for dissolved zinc was 68%, which is notable considering that zinc is quite soluble. One of the keys to the success of the MCTT was the proper sequencing of the components

The 2001 Ecology Stormwater Manual requires treatment trains for a number of types of stormwater runoff. These typically take the form of two full-sized treatment systems in series, such as a Biofiltration swale followed by a sand filter. While the concept may appear sound, for some of the combinations proposed in the 2001 Ecology Manual there is no evidence that pollutant removal will increase significantly above application of the individual BMPs alone (Minton 2004e). Furthermore, with some combinations, maintenance problems may occur. For the example given above, erosion within the swale will cause premature clogging of the sand filter.

Sweeping

While the Nationwide Urban Runoff Program, or NURP (USEPA, 1983) found that traditional mechanical sweeping was not effective in reducing stormwater pollution, increasing attention in the past decade has been focused on high-efficiency sweeping technologies. Minton (1999) pointed out that, in fact, mechanical sweepers provided water quality benefits in thirty of the fifty cases investigated, and all five of the pollutants monitored in Bellevue WA were thought to have been reduced by sweeping. However, none of the reductions due to sweeping was greater than 50%, which was not deemed adequate by the NURP researchers. Furthermore, dramatic increases of pollution occurred in tests in North Carolina, probably due to removal of the larger surface sediments and exposure of underlying fine, pollutant-rich sediments (Minton 1999). These findings led to the overall conclusion by the USEPA that sweeping was ineffective (USEPA, 1983).

Minton (1998) discussed modeled street pollutant removal using performance data from various kinds of high-efficiency sweepers, which utilize strong vacuums and mechanical sweepers to remove solids from the roadway, combined with air filtration. The model used was calibrated with results in Portland OR (Sutherland and Jelen 1996). Minton's modeled results showed that high-efficiency sweepers were significantly more effective in removing street solids than a mechanical sweeper. Sweeping is likely the most cost-effective method to reduce non-point pollution, on the order of 10 to 20% of the cost of treatment systems (Minton 2002b Sutherland et al. 1998). It also has the advantage of being applicable to currently developed areas without capital construction modifications of the storm sewer and adjacent land surfaces.

Comparison of different stormwater treatment systems

As discussed by Minton (2002a), the extreme variability of stormwater quality, the very low concentrations for most pollutants, and difficulties inherent with field sampling make the comparison of treatment systems of the same or different types problematic and statistically challenging. A related issue, much discussed among water resource professionals, is the lack of a commonly-accepted performance standard for treatment systems. The establishment of performance standards is in large part a policy issue as well as a technical issue.

The 2001 Ecology Stormwater Manual sets forth percent-removal goals for TSS, petroleum, and phosphorous, but does not set forth such a goal for dissolved metals, due to "the sparse data concerning dissolved metals removal in stormwater treatment facilities." However, Ecology states that "[T]he Enhanced Menu (i.e., metals removal) facility choices are intended to provide a higher rate of removal of dissolved metals than Basic Treatment facilities." The Basic Treatment facilities are essentially those required in the 1992 Ecology Manual; in the parlance of the 2001 Manual, 'basic treatment' is equivalent to 50% TSS removal with certain qualifications. Thus, for dissolved metals removal, the conundrum remains of how to determine whether a system not found in the 2001 Ecology Manual is adequate.

Consideration of the 'design storm'

The question of the proper 'design storm' is also a policy issue to a significant degree, because it is driven in part by the decision of a minimum threshold of 'adequate' treatment. Designing stormwater treatment systems to treat the entire annual volume of stormwater is considered to be impractical from a public policy perspective, and there is some scientific basis for this sentiment. The 1992 Ecology Stormwater Manual required treatment design on the basis of either the volume or the peak flow from the 6-month 24-hour storm calculated by a single-event hydrologic model. The rationale was that approximately 90% of the annual rainfall volume in the Puget Sound area occurs during such storms, and that designing larger systems would not be a sound return on investment. The 2001 Ecology Manual takes a similar approach to system sizing, although it sets forth more stringent requirements for treatment system design relative to the 1992 edition, in the form of requiring larger systems for the same flow rate, or treatment trains. It has recently been proposed that the Ecology procedure significantly oversizes wet ponds, vaults and wetlands, based on national performance data and engineering principles (Minton, 2003).

Minton (2000a, 2000b) discussed the idea of requiring more stringent treatment for urban areas during the summer, which they define as June through October. His rationale is based on the following premises:

- in urbanized areas, water temperatures are higher in the summer, and thus the metabolic rates of aquatic organisms are higher;
- young fish in the streams are more vulnerable to toxic conditions;
- stream flows are lower, so an influx of polluted stormwater will be less diluted in the stream;
- pollutant concentrations may be highest in summer storm runoff; and
- organisms may be less adapted to summer stormwater flows, which did not typically occur in a forest condition.

The strategy would be accomplished by diverting summer runoff through a treatment train consisting of primary and secondary treatment units. The primary unit would be used during the winter, and both units would be used during the summer. The secondary unit would be comparatively small because the flood control detention basin stores and slowly bleeds the storm volume to the secondary unit. The costs of this strategy are similar to the traditional approach but would provide much higher treatment during the most critical time of the year with respect to stream water quality.

It is worthy to note that a "summer strategy" need not focus solely on enhanced treatment. Prior to development it is unlikely that streams in lowland Puget Sound ever experienced heightened flows during the summer months. Their occurrence now is likely a significant factor in the degradation of suitable conditions for aquatic biota and sensitive fish, particularly young-of-the-year. Hence, certain stormwater mitigation measures that may have little benefit during the winter may be of particular benefit during the summer; such measures include green roofs, cisterns, rain barrels, watershed revegetation, and partial infiltration and OGFC pavements. For example, as previously noted, vegetation may have at most a very modest effect on ET during the winter and therefore storm runoff. However, it likely has significant impact during summer and early fall months, thereby reducing the volume of runoff from summer storms.

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